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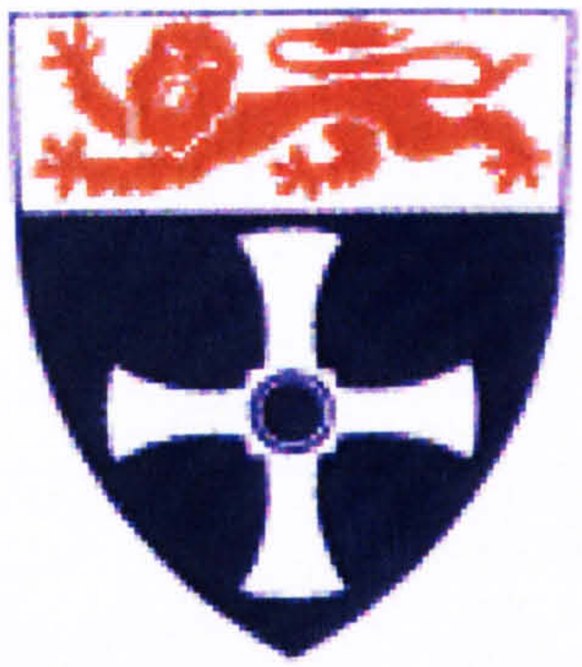

DESIGN AND MODELLING OF ELECTROOSMOTIC DEWATERING

by

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To my parents

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ABSTRACT

Many previous studies have demonstrated that electroosmotic dewatering is an effective technique to dewater sewage sludge. However, the technology has not yet been successfully applied in industry. This is because there are several technological barriers to the commercial exploitation of the technology that are yet to be resolved. One of these barriers is a scientifically robust design methodology. This aim of this study is to establish a qualitative and quantitative understanding model of electroosmotic dewatering of sewage sludge and from this produce a robust design methodology. This study is divided into three parts:

The first part evaluates the feasibility of electroosmotic dewatering under constant voltage for range of sludge types. A number of experiments with four different sewage sludges were undertaken to examine the dewatering efficiency in terms of rate of dewatering, final solid concentration and energy consumption. The results showed that electroosmotic dewatering of sludge is both feasible and potentially economic. It is also shown that the use of the Helmholtz-Smolucowski flow equation, together with the assumptions of no electrochemical reaction and a constant electroosmotic permeability, to predict the dewatering process is not sound.

The second part of this thesis presents an integrating framework for electroosmotic dewatering under constant voltage and constant current, founded on the mathematics of simple electrical circuits and demonstrated by laboratory experimentation. The derived equations and experimental results showed that electroosmotic flow rate decreases with time when dewatering with constant voltage and is constant when dewatering with constant current. Having a linear relationship between flow and time, electroosmotic dewatering with constant current not only enhances the sludge dewatering efficiency, but also has the advantage of simplifying design procedures.

The third part explores in further detail each of the design parameters of electroosmotic dewatering under constant current, including sample thickness, current, time over which constant current could be maintained, power supply, pressure and type of electrodes. A detailed design methodology, including design equations to predict final solid content and treatment time, design requirements for each parameter and design procedures, is presented.

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LIST OF SYMBOLS

Symbol	Explanation
A	Cross-sectional area
C	Capacitance of a capacitor
D	Dielectric constant
D	Diameter of sludge sample
E	Energy consumption per unit weight of extracted water
I	Electrical flow rate / Current
$I(t)$	Current with function of time
I_O	Initial current
J_D	Chemical flow rate
M	Total mass of the sludge in the cell
M_w	Weight of extracted water from sludge
Q	Charge
Q_e	Electroosmotic flow rate
R_D	Constant resistance
R_O	Initial resistance
R_V	Variable resistance due to electrochemical reactions
SD_1	Initial solid concentration of the sludge
SD_2	Final solid concentration of the sludge
V	Volume of the sludge in the cell
V	Voltage
$V(t)$	Voltage from the power supply with function of time
V_C	Potential difference across the capacitor C
V_D	Potential difference needed to generate the electroosmotic flow

Symbol	Explanation
V_{max}	Maximum voltage output of the power supper
V_O	Initial voltage
Vol	Volume of collected water
a	Single capillary of area
i_c	Chemical gradient
i_e	Electrical gradient (voltage gradient / current gradient)
i_h	Hydraulic gradient
i_t	Thermal gradient
k_h	Hydraulic conductivity
k_t	Thermal conductivity
m_c	Mass of chemically bound water
m_s	Mass of dry solid
n	Porosity
q_a	The quantity of water moved in unit time through a single capillary of area by electroosmosis
q_t	Heat flow rate
t	Processing time
t_b	Time over which constant current could be maintained
v_e	Electroosmotic velocity of water flow through the soil
ΔH	Head difference
ΔL	Distance between electrodes
ΔV	Electric potential difference
$\Delta V_{external}$	Voltage provided by the power supply
ξ	Zeta potential
ε	Dielectric constant of pore fluid

Symbol	Explanation
μ	Viscosity
σ_e	Electrical conductivity
ρ	Resistivity
ρ_s	Density of the sludge

CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

The treatment of sewage inevitably involves the creation of sewage sludge and the disposal of this sludge is one of the most problematical issues affecting wastewater treatment in the developed world. To provide an idea of the scale of the problem, in the UK a medium size sewage treatment works with a population equivalent of say 100,000 produces approximately 50,000 tonnes of liquid per year, or 137 tonnes per day.

The traditional outlets for sewage sludge were to spread it on agricultural land, to form a cake for deposit to landfill or incineration. However, the cheapest route has been to dig a lagoon on the site of the sewage works and pump the liquid sludge into it. Until very recently it was still legal to permanently deposit sludge produced at a sewage works in a lagoon at the works, but it was not legal to do so with any sludge imported to the works. This practice was only stopped by the recent EU Landfill Directive (Council Directive 1999/31/EC); it is now illegal to create new permanent unlicenced sludge lagoons or to put more sludge into any existing ones. There also have been new restrictions placed on spreading sludge to agricultural land imposed by the 'safe sludge matrix'. Thus, increasingly more emphasis will be placed on creating sludge cake for deposit to landfill or incineration.

In order to create a sludge cake, water must be removed and the solids content increased. This can be carried out by belt or filter presses. The problem with any of these devices

is that the water that can be extracted from the sludge by hydraulic means is limited. This is because of the way in which water is bound to the sludge particles or flocs. According to Smollen and Kafaar (1994), water exists in the following physical states:

1. Free: water not associated with solid particles
2. Interstitial, capillary: mechanically bound water which is trapped in the flocs
3. Vicinal: physically bound multiple layers, held tightly to the particle surface by hydrogen bonding
4. Chemically bound: water of hydration.

Existing dewatering technology based on mechanical compression can only remove free and interstitial water. Therefore, once a cake has been formed, however bad the quality, there are few ways of dewatering it further. This is a particular problem for activated sludge, which contains a large amount of vicinal and chemically bound water, which can support bacterial and other pathogens. Currently only thermal methods can remove interstitial and vicinal waters, involving high capital and operating costs.

For sludge disposal to landfill or incineration, the amount of water associated with the sludge is critical to the economics of the solution; transportation of water represents wasted energy in consumed fuel, and incineration requires a greater energy input to initiate the process. Due to the high water content of sludge, it is both economically attractive and technologically feasible to decrease the water content in order to reduce transport and disposal costs (Raats et al, 2001). Therefore there is an increasing demand for a more effective means of dewatering sewage sludge.

Most sludge materials have a slight electric charge relative to water; hence, when subjected to an electric field, the solid particles are attracted to one electrode while the

water migrates through the capillary matrix towards the opposite electrode (Orsat et al., 1999). The transport of water through porous media under the influence of an electric field is called as Electroosmosis, one of a group of Electrokinetic Phenomena. Electroosmotic flow within these materials is induced by the migration of ions and is independent of the hydraulic conductivity of sludge, which is very low. Therefore, electroosmotic dewatering is an efficient method to dewater within fine-grained low permeability sludge materials. Many researchers (Heath and Demirel, 1984; Kondoh et al., 1990; Yoshida and Yukawa, 1988; Golla et al., 1992; Yoshida, 1993; Gazbar et al., 1994; Smollen and Kafaar, 1994; Chen et al., 1996; Banerjee and Law, 1998; Barton et al., 1999; Gingerich et al., 1999; Orsat et al., 1999; Hansen et al., 2001; Larue et al. 2001; Zhou et al., 2001; Raats et al., 2002; Yuan and Weng, 2002) have shown that electroosmotic dewatering of sludge is more efficient than conventional hydraulically driven methods, such as belt and filter presses. The degree of dewatering can be enhanced by the combination of an electric field and pressure.

The positive effect of electroosmotic dewatering of sludge has been known for several years. However, the technology has not yet been successfully applied in industry. It is because there are several technological barriers to the commercial exploitation of the technology that are yet to be resolved. One of these barriers is a scientifically robust design methodology.

1.2 AIM AND OBJECTIVES

The aim of this research is to establish a qualitative and quantitative understanding design model of electroosmotic dewatering of sewage sludge system. The objectives of this research are to: (1) evaluate the feasibility of electroosmotic dewatering under constant voltage for range of sludge types and determine the electroosmotic dewatering efficiency in terms of dewatering rate, energy consumption and final solid content; (2)

present an integrating framework for the design of electrokinetically enhanced dewatering of sludge, which is more accurate than the existing design equation (Helmholtz-Smoluchowski flow equation) for practical use, and demonstrate its applicability through an experimental programme; (3) explore in further detail each of the parameters that constitute the design framework and; (4) present a detailed design methodology.

1.3 STRUCTURE OF THE THESIS

Chapter 1 introduces the background of electroosmotic dewatering, states the aim and objectives of the research and gives a brief summary of the contents of the thesis.

Chapter 2 summarises the literature review on electroosmotic dewatering. It includes objectives of dewatering, sludge-liquid phase, conventional dewatering techniques, the concept and theory of electrokinetic phenomena relating to sludge, electrochemical reactions, details of electroosmotic dewatering and brief descriptions of previous studies on electroosmotic dewatering.

Chapter 3 evaluates the feasibility of electroosmotic dewatering under constant voltage for range of sludge types. A number of experiments to examine the efficiency of the dewatering process in terms of dewatering rate, energy consumption and final solid content are presented. A detailed discussion with of the experimental results is also provided.

Chapter 4 presents an integrating framework for the design of electrokinetically enhanced dewatering of sludge and demonstrates its applicability through an experimental programme. The experiments include electroosmotic dewatering of sludge with constant voltage and constant current. The experimental results are

presented and discussed.

Chapter 5 derives design equations to estimate treatment time and final solid concentration of sludge, explores in further detail each of the parameters that constitute the design framework and presents a more detailed design methodology. The experimental testing and results covering the investigation of the effect of applied pressure, sample thickness, different currents and different electrode materials are given and then followed by a detailed discussion.

Chapter 6 presents a summary and the conclusions of the research. Recommendations for further research are given. The fulfilment of the research objectives is discussed.

CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

Dewatering of sludge is a process to remove water before disposal. Due to the physical and chemical properties of the sludge, removal of water cannot be easily carried out by mechanical compression alone. Disposal of sludge has become a problem facing the whole of the industrialized world. Increasing environmental and economic pressures mean that there is a demand for more effective means of dewatering of these materials than the traditional mechanical means.

The first successful application of electrokinetic phenomena to civil engineering processes was undertaken by Casagrande in 1939 for the dewatering and stabilization of railway cuttings at Salzgitter, Germany (Casagrande, 1952). Since then, the research on electroosmosis has been extended to geoenvironmental engineering applications such as the dewatering of sludge. It has been found that electroosmosis can be applied to remove water from sludge and a variety of other fine particulate materials efficiently.

This chapter summarises a literature review on electroosmotic dewatering. Included are details relating to: the objectives of dewatering, sludge-liquid phase; conventional dewatering techniques; the concept and theory of electrokinetic phenomena relating to sludge; electrochemical reactions; details of electroosmotic dewatering and brief descriptions of previous studies on electroosmotic dewatering.

2.2 OBJECTIVES OF DEWATERING

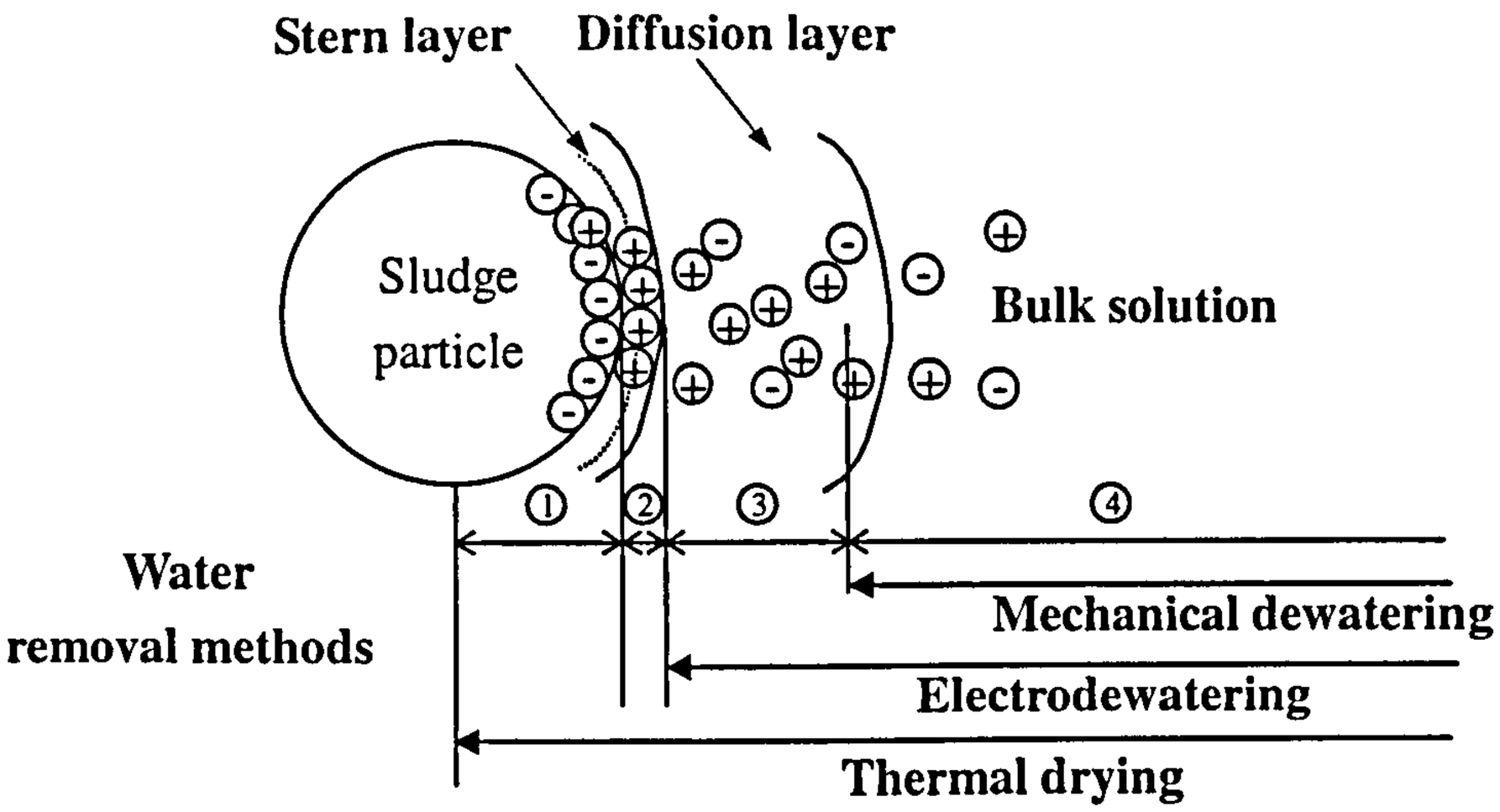
Sludges can be identified as the waste products from a range of industrial processes such as agricultural and animal wastes, sewage treatment, water purification residues and dredged materials. A common characteristic of different types of sludge is the very high water content, with only 1-5% solids on a mass basis (Raats et al., 2002). The objectives of dewatering include: (1) recovery of the product for sale in as dry a form as is practicable or as the market requires; (2) recovery of water for recycling; (3) the transformation of the waste into forms that are easily handled and can be safely disposed of, for environmentally-acceptable landfills and different recreational uses, such as football pitches and golf courses (Lockhart, 1992).

2.3 SLUDGE-LIQUID PHASE

According to Smollen and Kafaar (1994), all sludges consist of a combination of a solid phase with a certain quantity of water. There are different physical forms of water in sludge and these different forms play an important role in determining the ease or difficulty of phase separation. The descriptions of different physical forms of water in sludge are:

1. Free: water not associated with solid particles;
2. Interstitial, capillary: mechanically bound water which is trapped in the flocs;
3. Vicinal: physically bound multiple layers of water molecules, held tightly to a particle surface by hydrogen bonding;
4. Chemically bound or water of hydration.

Conventional dewatering techniques, such as vacuum filter, belt filter press and centrifuge, which are based on mechanical pressure, are effective in removing the free water. Electroosmotic dewatering, which is based on electroosmosis, can be



Water distribution		
① Chemically bound	③ Vicinal	
② Capillary	④ Free	

Figure 2.1 Dewatering methods in relation to water distribution in the sludge (After Zhou et al., 2001)

applied to remove free, vicinal and capillary water. Dry solid sludge particles can be achieved by thermal drying. The dewatering methods in relation to a sludge-liquid phase are shown in Figure 2.1.

2.4 CONVENTIONAL DEWATERING TECHNIQUES

In order to lower the cost of transportation and disposal, sludge is best dried out to remove as much liquid as possible before disposal. Dewatering can be achieved via some conventional dewatering techniques based on application of mechanical forces, such as vacuum filters, belt filter presses and centrifuges.

2.4.1 VACUUM FILTRATION

Vacuum filters are widely used to dewater low solids slurries, wherein the solid constituent in a slurry is separated by a porous filter cloth rotated through the slurry, with vacuum applied to the inner surface to cause the solids to accumulate on the surface as a cake.

The process consists of a rotary drum filter, vacuum pump, filtrate tank and scraper blade. In the vacuum filtration process, the slurry is drawn to the surface of the drum, which is covered with a filter material, holding the solids and allowing the liquid to enter the drum. The liquid is pulled by the vacuum flow to a filtrate tank. A vacuum is applied to the drum as the drum rotates, drawing air through the solids on the drum face and further reducing their moisture content. Just prior to discharge, a blast of compressed air is used to push the solids away from the drum surface, thereby allowing the scraper blade to operate effectively without tearing the filter material on the drum surface.

2.4.2 BELT FILTER PRESS

Belt filter presses are commonly used to dewater sewage sludges. They consist of two endless filter cloths belts, which encapsulate the sludge. Drainage is achieved by causing the belts to move closer together thereby applying mechanical pressure to the sludge. This is done by passing the belts over a number of closely spaced rollers.

There are three distinct phases in the process: (1) Pre-conditioning, (2) Preliminary drainage and (3) Secondary dewatering. In the pre-conditioning phase, the sludge is pumped into a mixer where it is conditioned by adding flocculants. The pre-conditioned sludge is then discharged into the preliminary drainage zone where the free water is drained by gravity through a porous belt. The sludge then passes to the secondary dewatering phase where it is compressed between the belts with increasing high pressure.

2.4.3 CENTRIFUGE

Centrifuge dewatering processes use centrifugal force to promote solid/liquid separation. The slurry is fed into a rotating basket assembly and accelerated. Solids are pulled out

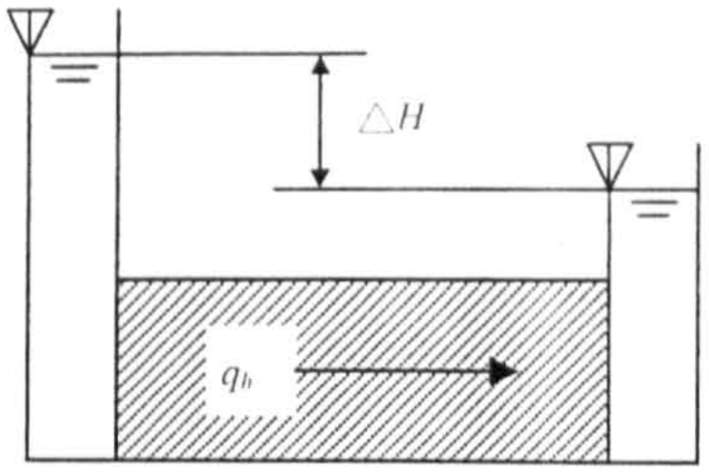
of the slurry by centrifugal force and are collected on the basket wall. The separated liquid flows out of the basket and is collected in the centrifuge housing, before being discharged.

2.4.4 DISADVANTAGES OF CONVENTIONAL DEWATERING TECHNIQUES

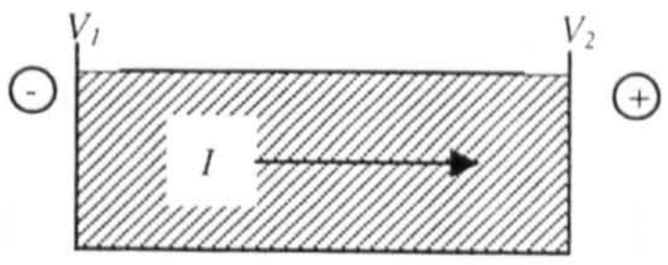
The major disadvantage of the conventional hydraulically driven dewatering techniques is that the dewatering rate depends on the pore diameter in the sludge, i.e. on its hydraulic permeability. During mechanical dewatering, the layer of sludge near the filter medium is compressed, thus reducing the porosity in that layer. Blocking of the filter medium occurs and consequently the dewatering rate gradually decreases with time (Yoshida, 1993). As a result, conventional dewatering techniques are not efficient methods to dewater sludges with low hydraulic permeabilities.

2.5 CONDUCTION PHENOMENA

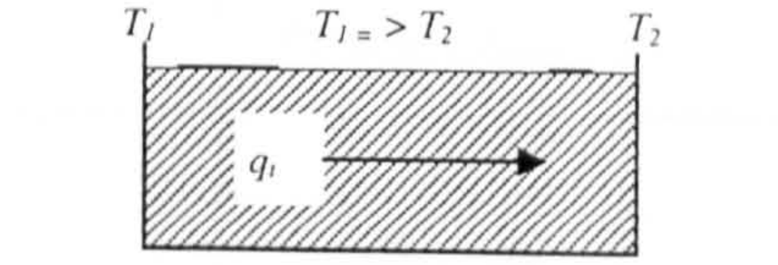
Several types of flows may exist within sludge systems. The types of flow can be categorised into 4 groups, identified as hydraulic, electrical, chemical and thermal flows. Provided the flow process does not change the state of the sludge, each flow rate or flux is linearly related to its corresponding driving force (Mitchell, 1991). The equations for hydraulic, thermal, electrical and chemical flows are governed respectively by Darcy's Law, Fourier's Law, Ohm's Law and Fick's Law. The four types of flow and their governing flow equations are shown in Figure 2.2. In the equations presented in Figure 2.2, q_h, q_t, I and J_D are the water, heat, electrical and chemical flow rates. The coefficients k_h, k_t, σ_e, and D are the hydraulic, thermal and electrical conductivities and the diffusion coefficient. The driving forces for flow are given respectively by the hydraulic, thermal, electrical and chemical gradients, i_h, i_t, i_e and i_c.



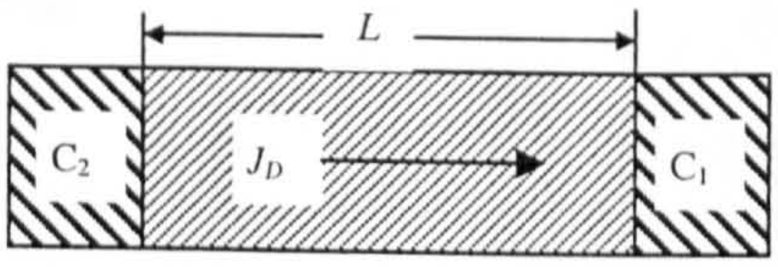
$$q_h = k_h\, i_h \qquad \text{(Darcy's Law)}$$



$$I = \sigma_e\, i_e \qquad \text{(Ohm's Law)}$$



$$q_t = k_t\, i_t \qquad \text{(Fourier's Law)}$$



$$J_D = D\, i_c \qquad \text{(Fick's Law)}$$

Figure 2.2 Four types of direct flow through a soil mass and their equations
(After Mitchell, 1991)

2.5.1 COUPLED FLOWS

In most cases, there are simultaneous flows of different types, even when one type of driving force is acting (Mitchell, 1991). For example, when water containing chemicals flows under a conventional hydraulic gradient, there is an associated flow of chemicals with the hydraulic flow. The types of coupled flows that can occur are given in Table 2.1.

2.6 ELECTROKINETIC PHENOMENA

Electrokinetic phenomena were first observed by Reuss in 1809. Water was observed to move through capillary pores towards the cathode when a direct current (DC) potential difference was applied to a clay water mixture. When the electric potential was removed, the flow of water immediately stopped.

Table 2.1 Direct and coupled flow phenomena (After Mitchell, 1991)

Flow	Gradient			
	Hydraulic head	Temperature	Electrical	Chemical concentration
Fluid	Hydraulic conduction: Darcy's law	Thermo-osmosis	Electro-osmosis	Chemical osmosis
Heat	Isothermal heat transfer	Thermal conduction: Fourier's law	Peltier effect	Dufour effect
Current	Streaming current	Thermo-electricity: Seebeck effect	Electric conduction: Ohm's law	Diffusion and membrane potentials
Ion	Streaming current	Thermal diffusion of electrolyte: Soret effect	Electrophoresis	Diffusion: Fick's law

There are five principal electrokinetic phenomena associated with porous media. They are: Electroosmosis, Electrophoresis, Ion Migration, Streaming Potential and Migration Potential. The first three of these phenomena are concerned with transport mechanisms developed upon application of an electrical field across a particulate mass. The remaining two are concerned with the generation of electrical potential due to the movement of charges and charged particles respectively.

Most sludge materials have a slight electric charge relative to water (Orsat et al., 1999) and sludge particles are negatively charged (Smollen and Kafaar, 1994). To balance this charge, a row of cations from the solution line up along the sludge particle surface.

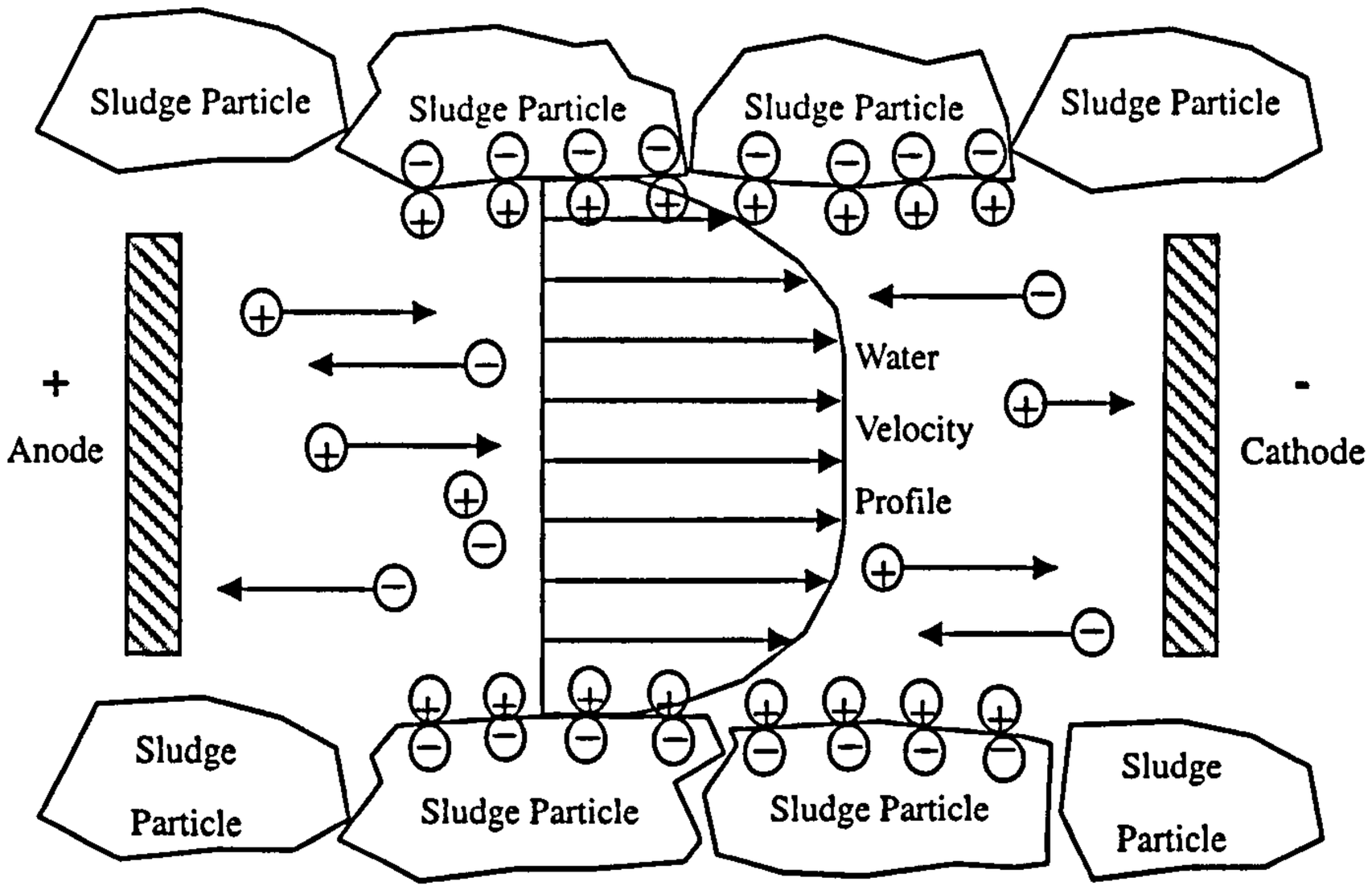


Figure 2.3 Principle of Electrokinetics

The combined system of the surface charge on the particle and the corresponding counter ion charge in the solution is known as a double layer. Under the influence of an electric field, the rows of cations on the sludge particle surfaces start migrating towards the cathode by electrical attraction. The movement of this boundary layer of cations drags the bulk water within the sludge with it. The transport of water from the anode to the cathode is called Electroosmosis. Within the bulk water of the sludge, the individual cations also move towards the cathode and the anions move towards the anode. This ion movement is called Electromigration. Moreover, the charged particles and colloids in solid-liquid mixture under electric potential gradient are attracted to the oppositely charged electrode. This migration of charged particles is called Electrophoresis. The principal electrokinetic processes are shown in Figure 2.3.

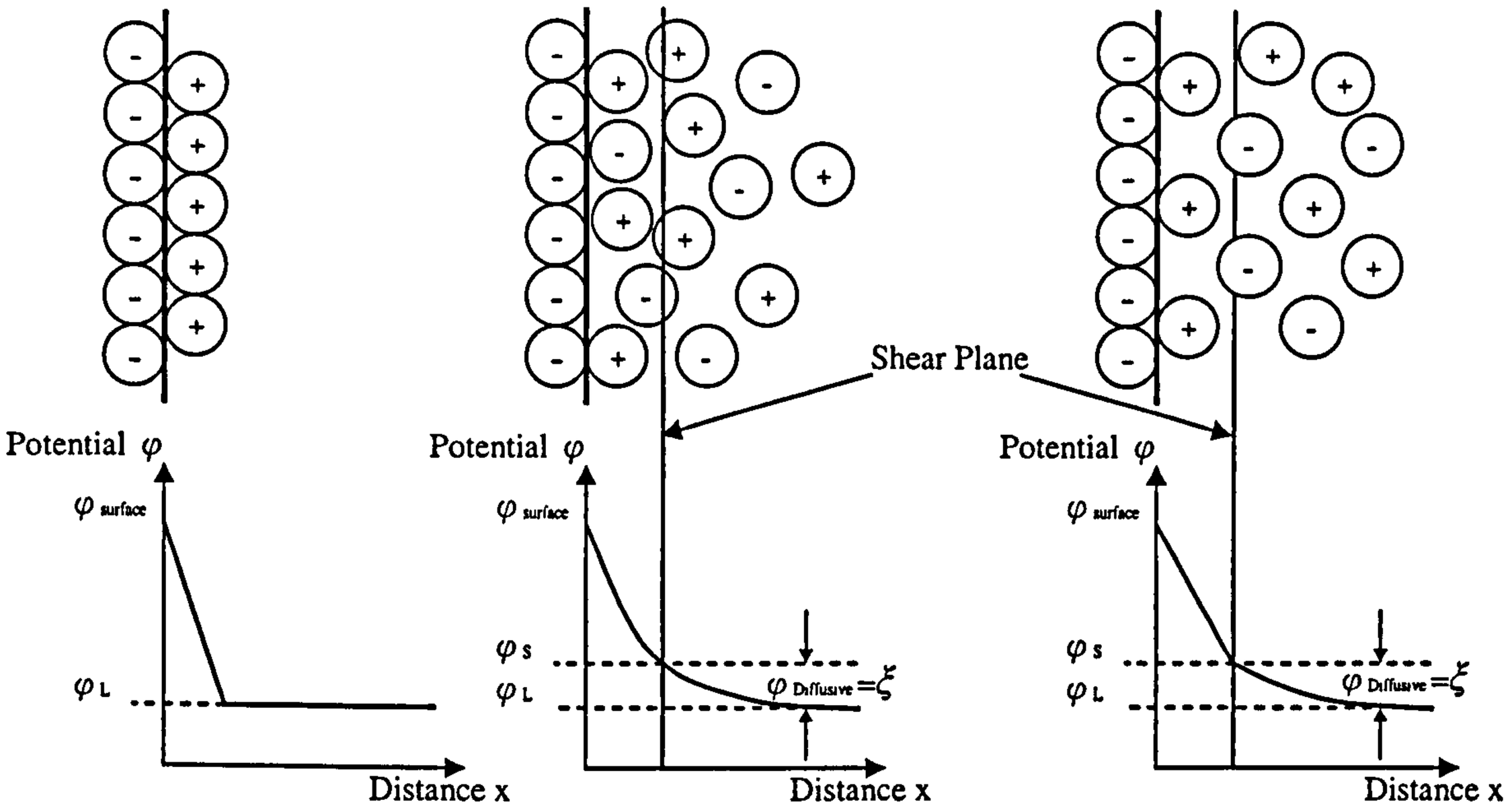
2.6.1 DOUBLE LAYER

Electroosmotic dewatering is based on electrically induced flow, which is possible because of the presence of the double layer at the sludge-liquid interface. Double layer theory is an important concept for understanding the principle of electrokinetic phenomena.

Due to the negative charge of sludge particles, the cations in solution are attracted to the particle surface by electrostatic attraction in order to balance the surface charge, when the sludge particles are in contact with electrolytic solution. The combined system of the surface charge on the particle and the corresponding counterion charge in the solution is known as double layer. The model of a double layer was first put forward in the 1850's by Helmholtz (1879). In the model of Helmholtz, the negative charge potential is linearly dissipated from the surface to the cations balancing the surface charge (Helmholtz, 1879). However, the model does not account for the diffusion factor.

The distribution of the adsorbed cations is not uniform throughout the liquid phase and the concentration of the adsorbed cations near the surface of the particle is much higher. Gouy (1910) and, independently, Chapman (1913) developed theories of diffuse double layer in which the change in concentration of the counter ions near a charged surface follows a Boltzmann distribution. In the model of the diffusive layer of Gouy-Chapman, the negative charge potential is exponentially decreased with the distance into the bulk solution. The Boltzmann distribution assumes that activity is equal to the molar concentration. The Gouy-Chapman model is valid for the bulk solutions with low concentration of ions of opposite charge, but not valid near a charged surface where high concentrations of ions of opposite charge are present.

Stern (1924) modified the Gouy-Chapman diffuse double layer model. He combined the models of Helmholtz and Gouy-Chapman. According to the Stern model, the double layer consists of a fixed part and a diffused part. In the fixed double layer where is high concentration of counter ions, the Stern model follows the Helmholtz approach. With low concentrations of counter ions, the Stern model follows the Gouy-Chapman model. The boundary between the fixed and diffuse double layers is



(a) Fixed double layer by Helmholtz

(b) Diffuse double layer by Gouy-Chapman

(c) Fixed and diffuse double layer by Stern

Figure 2.4 Models of the double layer (After Weber and Stahl, 2002)

called the Stern layer and the potential difference between the Stern layer and the interior of the liquid is called the Stern potential. Models of the double layer theories are shown in Figure 2.4.

The thickness of the diffuse double layer is an important parameter in determining the extent of interaction between charged colloidal particles, and depends on the concentration of ions in the solution. In concentrated solutions, the thickness of the diffused double layer is small (< 1nm) whereas in very dilute solutions, the diffuse double layer can assume much a larger value (~10^2 – 10^3nm) (Vijh, 1999).

2.6.2 ZETA POTENTIAL

When a particle moves within a liquid under the effect of an applied electric field, a plane of shear is formed around the particle. The electrical potential difference between the plane of shear and the bulk solution is called the zeta potential (ζ), as

shown in Figure 2.4. The exact location of the zeta potential cannot be quantitatively determined by existing theories (Shang, 1997c). In a first approximation, the plane of shear lies in the Stern layer, and the zeta potential is often considered as equal to the Stern potential (Weber and Stahl, 2002). Shang (1997c) investigated the relationship between the electroosmotic permeability and the zeta potential. In these studies, the computed zeta potential is assumed to be the electrical potential at distance $x = 0.6$nm, compared with the location of the Stern potential at distance $x = 0.5$nm.

The zeta potential is an important factor affecting electroosmotic flow. According to the Helmholtz-Smoluchowshi theory (see Section 2.6.3.1), the electroosmotic flow is proportional to the zeta potential. For a sludge with a large zeta potential, the water removal rate tends to be larger (Chen et al., 1996).

The zeta potential is affected by the ion concentration, the pH value of the fluid and the sludge conductivity. If the ion concentration is too high, the zeta potential is reduced so that the electroosmotic flow rate decreases (Lockhart, 1992). The addition of various ionic solutions can modify the magnitude of the zeta potential thus modifying the electroosmotic flow (Orsat et al., 1999). Rabie et al. (1994) showed that changes in pH caused by the electrode reaction affect the rate of water removal by changing the zeta potential during the electroosmotic dewatering process. Gazbar et al. (1994) showed that the increase of the sludge electrical conductivity reduces the zeta potential at the surface of the solid phase of the sludge. The electrochemical reactions occurring during the dewatering process, which affect the zeta potential, are discussed in Section 2.6.4.

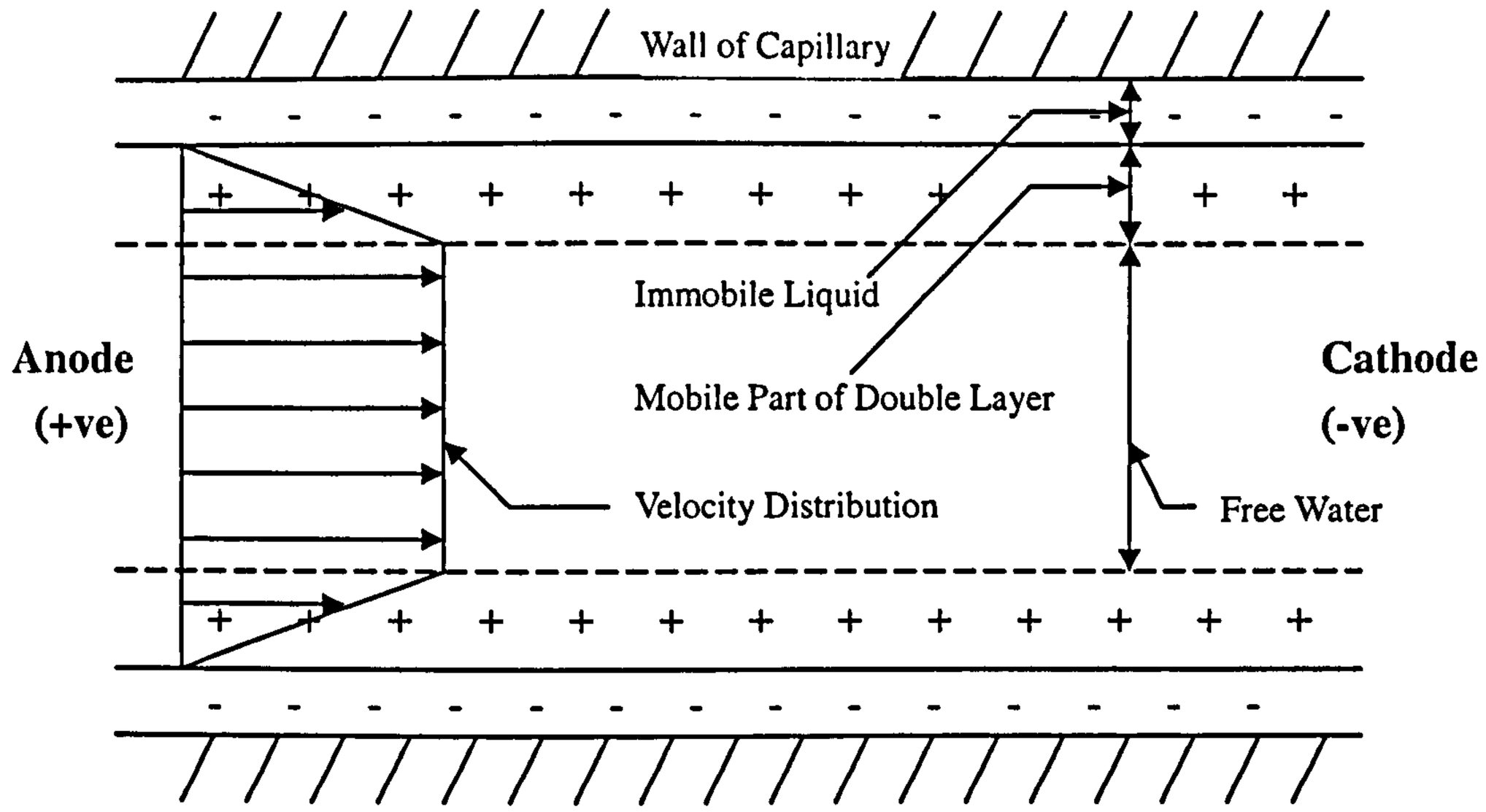


Figure 2.5 Electroosmotic flow in rigid-straight capillaries

2.6.3 ELECTROOSMOSIS

Electroosmosis, which is the phenomenon of principal interest in this thesis, is the main mechanism of water transport through a fine-grained porous media under the influence of a direct current (DC) electric field. Casagrande (1952) explained the mechanism of electroosmotic flow of water in rigid and straight capillaries (see Figure 2.5) as follows:

"At the solid-liquid interface opposite charges are oriented in such a manner that either negative or positive ions are adsorbed on the wall of the capillary while ions of opposite charge remain in the liquid forming an adjacent and parallel layer. If such a capillary is placed into an electric field, the ions contained in the inner layer, which forms part of the liquid phase, will move towards the electrode of opposite sign and drag along the free water enclosed by this moving boundary film."

2.6.3.1 HELMIIOLTZ-SMOLUCHOWSKI THEORY

Helmholtz (1879) first provided a mathematical model for the analysis of electroosmosis, based on observations of a single capillary. He stated that the rate of water flowing through the capillary is controlled by an electrical force causing the

movement of water, which is countered by friction between the water and the wall of the capillary. Later, Smoluchowski (1921) produced a modified version of the Helmholtz model. The Helmholtz-Smoluchowski (H-S) theory deals with electroosmotic/electrophoretic velocity of a fluid of certain viscosity and dielectric constant through a surface-charged porous medium of zeta potential, ξ, under an electric gradient. According to the H-S theory, the electroosmotic velocity can be derived based on the balance of the electrical and frictional forces between water and the wall of the capillary and is as follows:

$$v_e = \frac{\varepsilon\xi}{\mu}\frac{\Delta V}{\Delta L} \qquad \text{Equation 2.1}$$

where v_e is the electroosmotic velocity, ξ is the zeta potential, ε is the dielectric constant of pore fluid, μ is the viscosity, ΔV is the electric potential and ΔL is the length of the capillary between the electrodes.

2.6.3.2 ELECTROOSMOTIC FLOW AND PERMEABILITY

The quantity of water moved in unit time through a single capillary of area, a, by electroosmosis, q_a, is:

$$q_a = \frac{\varepsilon\xi}{\mu}\frac{\Delta V}{\Delta L}a \qquad \text{Equation 2.2}$$

Considering a prism of saturated porous medium mass (soil / sludge) with a base area, A, in contact with the electrodes and length, L, instead of a capillary, the electroosmotic flow, Q_e, becomes:

$$Q_e = \frac{n\varepsilon\xi}{\mu}\frac{\Delta V}{\Delta L}A \qquad \text{Equation 2.3}$$

where n is the porosity (dimensionless).

The electroosmotic flow of water through a porous medium, Q_e (cm^3/s), can be expressed in the form of Darcy's equation for water flow:

$$Q_e = k_e i_e A \qquad \text{Equation 2.4}$$

where $k_e = \frac{\xi D}{\mu} n$ and is the coefficient of electroosmotic permeability (cm^2/Vs), $i_e = \frac{\Delta V}{\Delta L}$ and is the electrical potential gradient (V/cm), A is the cross-sectional area (cm^2), D is dielectric constant (dimensionless).

In order to generate a substantial level of electroosmotic flow, the electric field strength has to be strong enough to electrolyze water. Grundl and Michalski (1995) stated that electric field strengths of 100V/m (1V/cm) or less are sufficient to generate electroosmotic flow.

The electroosmotic permeability, k_e, depends mainly on the pore area and is independent of the size of the individual pores, whereas hydraulic permeability is very strongly influenced by the actual pore size (Casagrande, 1949). The electroosmotic permeability is not a constant. This is because the application of an electric field not only generates electroosmotic flow, but also the associated electrochemical reactions. Over time, these reactions directly change the zeta potential, and inspection of the H-S equation will result in a change in electroosmotic permeability.

2.6.4 ELECTROCHEMICAL REACTIONS

When applying a potential gradient across a sludge, current and electroosmotic flow

occur. The passage of the current causes electrochemical reactions at the two electrodes, identified as electrolysis. Due to electrolysis, the water is decomposed and gases are generated at the electrodes. The electrolysis reactions are:

Anode: $2H_2O \rightarrow 4H^+ + O_2\,(g) + 4e^-$ Equation 2.5

Cathode: $4H_2O + 4e^- \rightarrow 2H_2\,(g) + 4OH^-$ Equation 2.6

During the electrokinetic process, the electrolysis reactions result in the evolution of O_2 at the anode and H_2 at the cathode. The pH is reduced at the anode due to generation of H^+ and raised at the cathode due to OH^-. Consequently, water becomes acidic near the anode and basic near the cathode. Because of the bulk water flow from the anode to the cathode and the high ionic mobility of H^+ (nearly twice that of OH^-), the resulting acid front generated at the anode migrates through the sludge (Grundl and Michalski, 1995). These reactions result in a number of effects, such as changes in pH and zeta potential, generation of gases and increase in electric resistance. Changes in pH give rise to concentration gradients in the bulk of the sludge causing a change in zeta potential values near the electrodes, which in turn result in reduced electroosmotic flow (Vijh, 1995). The gases generated at the electrodes, which are non-conductive and difficult to be dissipated, increase the electric resistance. As a result, the dewatering efficiency is reduced.

2.6.5 ASSUMPTIONS OF ELECTROKINETIC ANALYSIS

As a result of electrochemical reactions, variations in electroosmotic permeability, which depends on the zeta potential and electric field, can be expected. In order to simplify the analysis of electrokinetic process, however, the electroosmotic permeability is assumed to be a constant and the effects of electrochemical reactions are ignored in

most mathematical models. Casagrande (1949) suggested that the electroosmotic permeability can be assumed to be a constant (k_e = 5 x 10^{-5}cm per sec. for 1 volt per cm) for most practical applications. In the analysis of electroosmotic water flow through soil, Esrig (1968) made the following assumptions:

1. The structure of the soil is uniform and the material is fully saturated;
2. The physical-chemical properties of the soil mass are uniform throughout and constant with time;
3. Electrophoresis of the fine-grained particles does not occur
4. There is a proportionality between the electroosmotic velocity of water flow through the soil, v_e, and the voltage gradient (electric field), $\Delta V/\Delta L$. The proportionality factor is called the electroosmotic permeability, k_e, which is assumed to be a property of the soil and to be constant with time;
5. All applied voltage is useful in producing water transport;
6. The electric field throughout the soil mass is not altered with passage of time;
7. No reactions (such as electrolysis) occur at the electrodes;
8. Fluid flows due to an electric field and those due to a hydraulic gradient may be superimposed to find the total flow.

The above assumptions are not necessarily correct in practical applications. This is the reason why the use of the Helmholtz-Smoluchowski flow equation together with these assumptions cannot predict the electroosmotic dewatering process accurately. A more accurate design framework will be explored in this research project.

2.6.6 ELECTROKINETIC APPLICATIONS

Since Casagrande first demonstrated the use of electroosmosis in 1939, a number of studies have shown that electrokinteic techniques are useful for different applications of

civil engineering. Electrokinetic applications can be divided into 3 categories, identified as:

1. Electrokinetic Remediation
2. Electrokinetic Sedimentation
3. Electrokinetic Dewatering

2.6.6.1 ELECTROKINETIC REMEDIATION

Electrokinetic remediation is a novel technique to remove metal, inorganic and organic contaminants electrically in low permeability soils (Shapiro and Probstein, 1993; Lageman et al., 1989; Bowman and Mattson, 1994; Acar and Alshawabkeh, 1996; Schultz, 1997; Alshawabkeh et al., 1999; Ho et al., 1999). Electrokinetic remediation uses electrochemical and electrokinetic processes to desorb and then remove metal and polar organics. With the application of a direct voltage across the soil, the charged species are mobilized, causing ions and water to move toward the electrodes. Metal ions, ammonium ions and positively charged organic compounds are attracted toward the cathode whereas anions, such as chloride, cyanide, fluoride, nitrate and negatively charged organic compounds move towards the anode. The rate and direction of the movement of ionic species depend on its charge, and the magnitude of the electroosmotic flow velocity. Non-ionic species, both inorganic and organic, are transported along with the electroosmotic flow.

2.6.6.2 ELECTROKINETIC SEDIMENTATION

Electrokinetic techniques can be used in wastewater treatment plants for the purpose of clarification of aqueous slurries. When electrodes are placed on the top and bottom of the slurry and the bottom electrode is made positive (anode), negatively charged particles will be attracted toward the bottom. This phenomenon is known as

electrophoresis. A number of experimental studies have shown that electrokinetic techniques increase the free settling velocity and final solid concentration, reduce the coefficient of sedimentation and overall sedimentation time, and are more effective that chemical coagulation (Shang 1997a, 1997b). The application of electrokinetics for treating slurries is called electrokinetic sedimentation.

2.6.6.3 ELECTROKINETIC DEWATERING

When a direct voltage is applied to a fine grained soil, the positively charged free water of the double layer is attracted towards the cathode and drags the bulk soil water towards the cathode as well. If there is no water replaced at the closed anode, negative porewater pressure will be developed, resulting in an increase in soil strength, which makes electrokinetic technique suitable for the improvement and stabilization of soil (Casagrande, 1949; Johnston, 1978; Morris et al., 1985; Lo et al., 1994). Moreover, the water flow within the fine-grained soil induced by electroosmosis is independent of the hydraulic conductivity of soil. Electrokinetic dewatering can be applied to accelerate the consolidation process (Nicholls and Herbst, 1967; Esrig, 1968; Wan and Mitchell, 1976; Shang, 1998; Mohamedelhassan and Shang, 2002) and the dewatering process for sludge (previous studies on electroosmotic dewatering of sludge are reviewed in Section 2.9).

2.7 ELECTROOSMOTIC DEWATERING OF SLUDGE

Electroosmotic dewatering is a novel technique to dewater sludge. The technique is most attractive when the water is trapped between fine solid particles and cannot be further removed efficiently by the application of pressure or vacuum (Vijh and Novak, 1997). This is because electroosmotic flow is based on the surface and colloid characteristics of particles in suspension, and is independent of pore size, in contrast to conventional hydraulic flow that falls off dramatically with pore size (Lockhart, 1992).

As a result, the low hydraulic conductivity of sludge and the resultant blocking of filter medium do not significantly affect the dewatering rate when applying electroosmotic dewatering. Therefore, electroosmotic dewatering is an efficient method to dewater low permeability sludges having hydraulic conductivity values less than 1 x 10^{-6}cm/s, compared to conventional dewatering methods (Mitchell, 1991). Usually, it is combined with mechanical methods to improve the rate and efficiency of dewatering.

2.7.1 ELECTROOSMOTIC DEWATERING PROCESS

According to Barton et al. (1999), electroosmotic dewatering involves both electrophoretic and electroosmotic phenomena and these effects have a major influence on both the rate and extent of dewatering. Electroosmotic dewatering is thought to comprise the following steps:

1. During the initial stages of dewatering, the particles are still free to move in the fluid suspension. Since the particles are usually negatively charged, they will be repelled by the cathode where the filter medium is located, thus delaying onset of cake formation at the cathode and reducing clogging of the filter medium, hence leading to enhanced water flow.
2. When the cake has formed, the particles are locked in position and hence unable to move. Under these circumstances, water is transported though the porous medium by electroosmosis. Electrochemical reactions and electrolysis at the electrodes occur due to the passage of current.
3. Eventually water will cease to flow within the cake, and the electrical resistance will rise leading to ohmic heating.

In principle, the achievement of complete water removal within the sludge is not possible. When a liquid stage in the sludge is no longer continuous as a result of

dewatering, the sludge does not conduct electricity and then electroosmosis ceases (Yoshida, 1993).

2.7.2 FEATURES OF ELECTROOSMOTIC DEWATERING

Yoshida (1993) has identified the main features of electroosmotic dewatering as follows:

1. The filter medium is not damaged and blocked so much and the effect of blocking on dewatering rate is very small.
2. The rate of dewatering and its efficiency are easily controlled by regulating the voltage applied to the sludge and electric current passing through the sludge.
3. Effective dewatering can be achieved in sludges which are not amenable to mechanical dewatering processes.
4. Electroosmotic dewatering can be easily combined with mechanical methods, leading to additional improvement in the rate and efficiency of dewatering.
5. Corrosion of the electrodes as a result of electrolysis can occur, resulting in subsequent contamination of the sludge.
6. When the electric conductivity of the sludge is very large, electric power efficiency becomes low because of the generation of heat. When conductivity is very low, a very large voltage is required to drive the flow. Therefore, the application of electroosmotic dewatering is restricted by the electrical properties of the sludge.

2.7.3 EFFICIENCY OF ELECTROOSMOTIC DEWATERING

The main advantages of electroosmotic dewatering include a high rate of dewatering and low energy consumption, compared to conventional dewatering methods. An assessment of the efficiency of electroosmotic dewatering can be expressed in terms of the dewatering rate and energy consumption.

2.7.3.1 EFFICIENCY IN TERMS OF DEWATERING RATE

A high dewatering efficiency can be achieved with sludges which cannot be treated mechanically. According to the Helmholtz-Smoluchowski theory (Section 2.6.3.1), the electroosmotic flow rate is a function of the strength of the electric field and the zeta potential.

An increase in water removal is obtained by increasing the electric field strength and the zeta potential. Increasing the electric field strength can be achieved by increasing the power output from the power supply. However, a high voltage gradient implies a high current, which can result in high rates of electrolysis reaction. The electrolysis of water generates gases at electrodes and causes changes in pH near electrodes. Difficulty in the dissipation of these gases can result in high local electrical resistance. Changes in pH near the electrodes give rise to concentration gradients in the bulk of the sludge, causing changes in zeta potentials near the electrodes. Both difficulties in the dissipation of gases and changes in pH result in loss of dewatering efficiency. However, a high zeta potential can be maintained by the addition of various ionic solutions to control the pH of the fluid.

Some researchers suggest that dewatering efficiency is related to the particle size of the sludge. Chen et al. (1996) conducted a series of experiments to investigate the efficiency of electroosmotic dewatering sludges with different particle sizes. They found that dewatering of sludges with small particle sizes to be most effective. Raats et al. (2002) analyzed the contribution of electroosmotic dewatering at different volume fractions of solids, and found that electroosmosis could contribute significantly to the dewatering of materials with small particle suspensions.

2.7.3.2 EFFICIENCY IN TERMS OF ENERGY CONSUMPTION

Electroosmotic dewatering process may be used as a precursor to further thermal dewatering processes. Thermal drying is achieved by heating the sludge with hot air. However, thermal separation processes such as evaporation release a significant volume of CO_2 and need a lot of energy (1kg of water needs approximately 1.2kWh to be evaporated). Therefore, researchers and engineers try to remove as much liquid as possible by economical means before using a thermal dewatering process. It is because further drying decreases the volume of the sludge, helping to minimize the environmental impact and the cost for thermal drying.

Compared to thermal drying, the energy consumption for electroosmotic dewatering is less, and from an environmental point of view, electroosmotic dewatering of sludge is beneficial in reducing the energy needed for complete evaporation of the remaining water (Raats et al. 2002). The energy consumption for electroosmotic dewatering of different materials given by different authors is shown in Table 2.2. The energy consumption for electroosmotic dewatering can be calculated based on the following equation:

$$E = \frac{\int VIdt}{M_w} \qquad \text{Equation 2.7}$$

where E is the energy consumption per unit weight of extracted water (kWh/kg of extracted water), V is the voltage (V), I is the current (A), t is the processing time (t), and M_w is the weight of extracted water from sludge (kg).

Water removal increases at higher electrical voltage, and from Equation 2.7 it is seen that energy consumption is directly related to the current, voltage and time. Therefore,

Table 2.2 Energy consumption given by different authors (Gazbar et al, 1994; Larue et al., 2001; Zhou et al., 2001; Golla et al., 1992; Banerjee and Law, 1998)

Author	Material	Energy Consumption (kWh/kg of extracted water)
Yukawa#	Clays (bentonite and kaolin)	0.05 – 0.1
Von Schwerin#	Peat	0.045
US Bureau of Mine#	Calcium phosphate	0.021
Deleuil#	Clay (kaolinite)	0.56
Elmtherm#	Slaughterhouse sludge	0.02 – 0.1
Zhou et al.	Waste activated sludge	0.013 – 0.119
Larue et al.	Highly conductive silica suspension	0.105 – 0.33
Gazbar et al.	Domestic anaerobically digested sludge	0.05 – 0.2
Banerjee and Law	Composted wastewater sludge	0.66
Banerjee and Law	Organic humus with peat	0.33
Golla et al.	Pharmaceutical sludge	0.25

References cited by Gazbar et al. (1994)

* The energy consumption given by different authors is variable. These differences are attributed to the nature of the material, to its initial concentration and especially to its final concentration.

** For comparison, 1kg of water needs approximately 1.2kWh to be evaporated.

a higher potential gradient would result in higher power consumption. During electroosmotic dewatering, electric resistance increases with time due to electrochemical reactions. The electric resistance of the bulk material being treated converts electrical energy into thermal energy, resulting in a temperature rise of the suspension or filter cake (Weber and Stahl, 2002). Therefore, high electric resistance implies high energy waste.

2.8 IMPROVEMENT OF ELECTROOSMOTIC DEWATERING

Electroosmotic dewatering has been shown to be an efficient technique to dewater sludge, compared to conventional dewatering techniques. However, the dewatering rate decreases with time due to electrochemical reactions. In order to minimize this problem, a number of procedures are possible.

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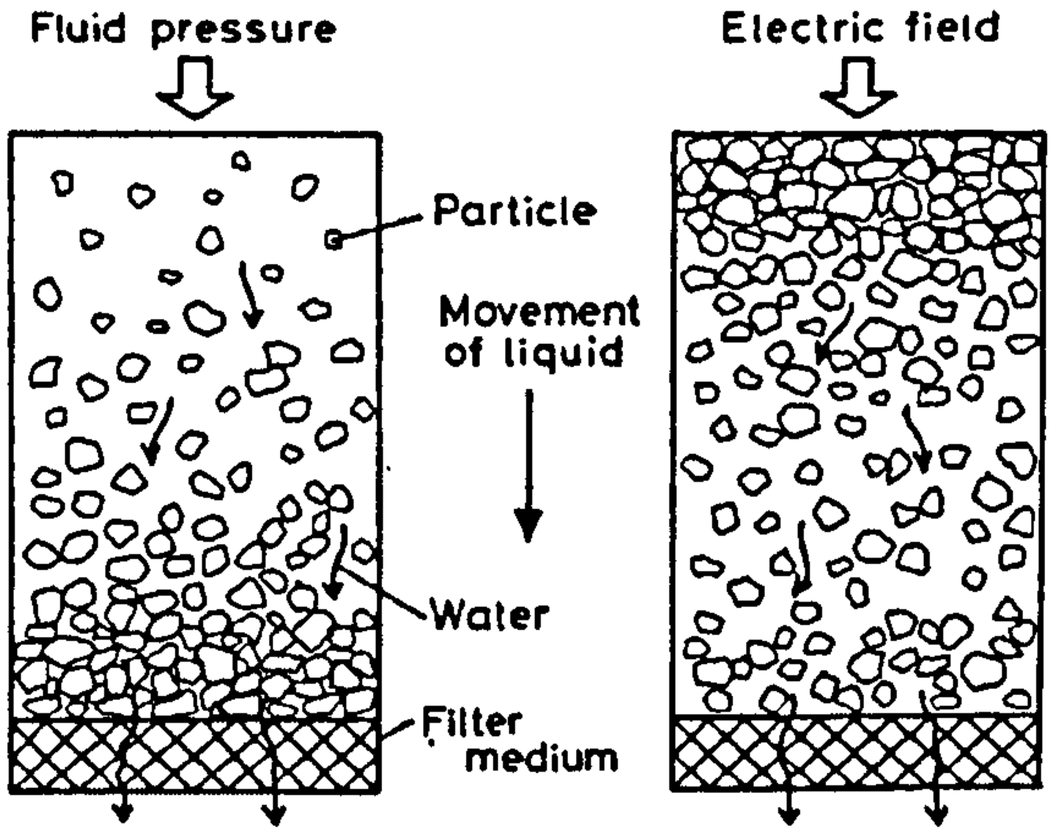
2.8.1 COMBINED FIELD DEWATERING

During mechanical dewatering, a layer of sludge in close proximity to the filter medium is developed, resulting in reduction of porosity in that layer, as shown in Figure 2.6a. This leads to blocking of the filter medium and consequently the dewatering rate gradually decreases with time (Yoshida, 1993). During electroosmotic dewatering, negatively charged particles are repelled by the cathode, thus reducing blocking of the filter medium (Barton et al., 1999). Moreover, due to electroosmotic flow from anode to cathode, the layer is dry at the top of the bed (in the vicinity of the anode) and wet at the bottom of the bed (in the vicinity of the cathode), as shown in Figure 2.6b. Drying of the anode region results in an increase in electric resistance.

To maintain electroosmotic dewatering efficiency, it is preferable that the strength of electric field is as uniform as possible everywhere in the sludge during the dewatering process (Yoshida, 1993). Since electroosmotic dewatering and mechanical dewatering



(a) Mechanical Pressure Dewatering (b) Electroosmotic Dewatering

Figure 2.6 Dewatering mechanism of sludge (After Yoshida, 1993)

are complementary, a combination of these dewatering operations can provide a more uniform dewatered bed, leading to improvement of the dewatering efficiency. Combined field dewatering is defined as a combination of applied external pressure and electroosmotic dewatering to remove water from a sludge or a comparable matrix of water trapped in colloidal suspension (Vijh and Novak, 1997). A schematic diagram of combined field dewatering is shown in Figure 2.7.

2.8.2 ELECTROCHEMICAL STRATEGIES FOR RESTARTING DEWATERING

During the electroosmotic dewatering process, changes in pH near the electrodes caused by the electrochemical reactions affects the rate of water removal by changing the zeta potential (Rabie et al, 1994). When the zeta potential drops to zero with increasing concentration of electrolytes in the pore water, the electroosmotic discharge of water ceases (Casagrande, 1949). Vijh (1995) has considered the effects of electrochemical reaction and suggested 5 strategies to restore the dewatering process and increase the energetic efficiency of the dewatering process:

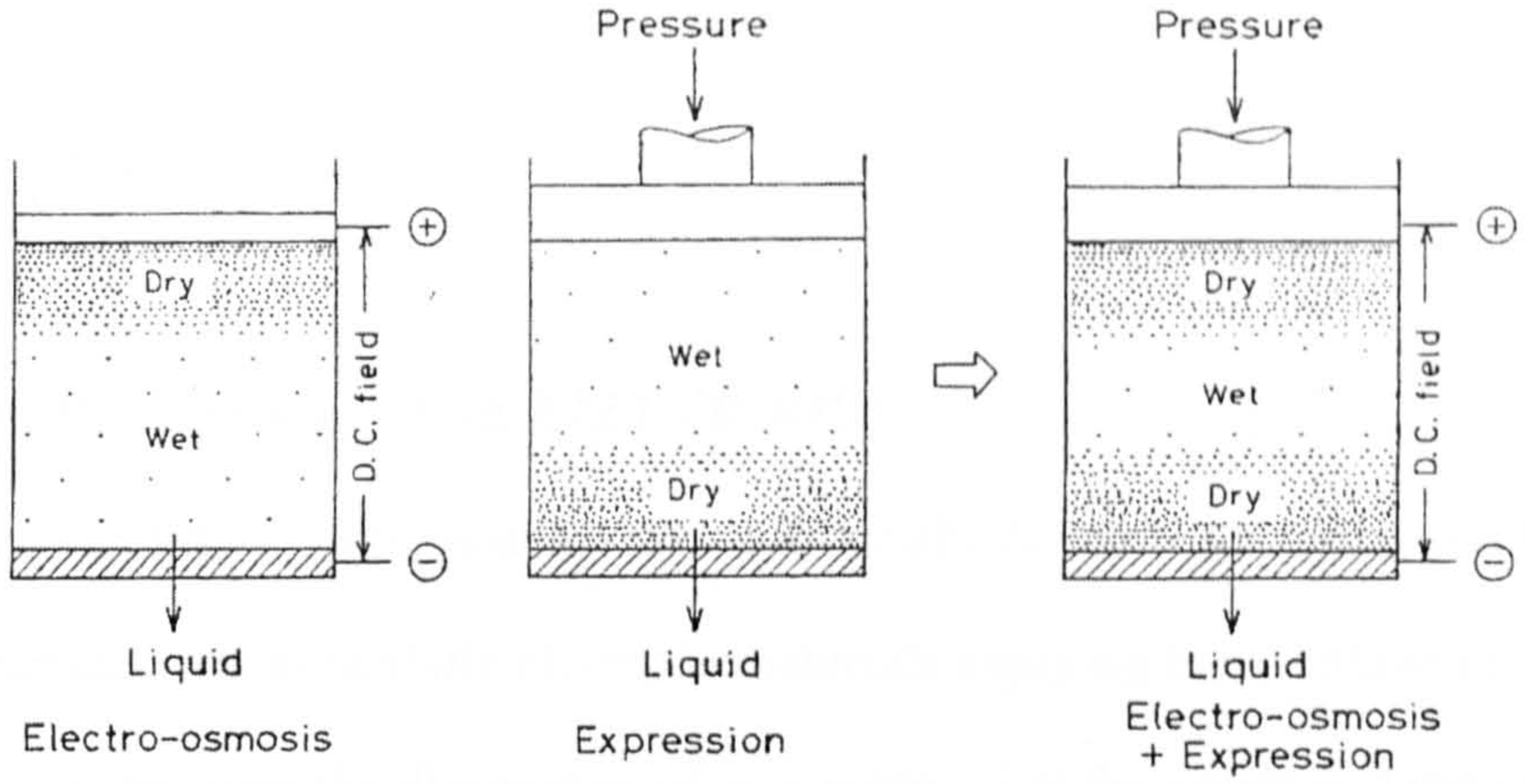


Figure 2.7 Schematic diagram of combined dewatering process of electroosmosis and expression (After Yoshida, 1993)

1. Fuel cell effects
2. Forced polarity reversal
3. High overvoltage electrodes
4. Maintaining high zeta potential
5. Depolarization of the anode reaction

2.8.2.1 FUEL CELL EFFECT

When the DC power is interrupted and the electrodes are short-circuited, a transient current, resulting from "discharge of an electrochemical cell", flows with an opposite direction to that during DC voltage application. During short-circuiting, the electrolysis reactions occurring when the DC power is on are reversed, causing the elimination of the zeta potential gradient and the restoration of the value of the zeta potential near the anode to a high value approaching that at the start of electrolysis.

2.8.2.2 FORCED POLARITY REVERSAL

The above fuel cell effect can be obtained more dramatically by reversing the DC voltage polarity. When the normal polarity for dewatering is restored, a high zeta

potential near the anode should be present, thus causing the re-commencement of electroosmotic dewatering.

2.8.2.3 HIGH OVERVOLTAGE ELECTRODES

The rates of electrode reactions at the anode and cathode could be minimized by using highly polarizable, non-catalytic electrode materials applying high voltage gradients. This results in delaying the diminution of zeta potential at the anode and the cessation of dewatering. For cathodes, metals such as Zn, Sn, Pb, In, Cd, Hg are suitable to minimize the rate of the hydrogen evolution reaction. For anodes, non-noble metals, alloys, carbides, and silicides can be used to minimize the oxygen evolution reaction.

2.8.2.4 MAINTAINING A HIGH ZETA POTENTIAL

Cessation of dewatering could be avoided by adding a small volume of concentrated NaOH (or KOH) solution to maintain a high pH and high value of zeta potential near the anode.

2.8.2.5 DEPOLARIZATATION OF THE ANODIC REACTION

During the electroosmotic dewatering process, the depletion of OH^- near the anode could be stopped by depolarizing the electrolysis reaction at the anode by another competing, parallel reaction such as:

$$Fe^{2+} \rightarrow Fe^{3+} + e^- \qquad \text{Equation 2.8}$$

$$2Cl^- \rightarrow Cl_2 + 2e^- \qquad \text{Equation 2.9}$$

2.8.3 ELECTROKINETIC GEOSYNTHETIC (EKG)

The application of electrokinetic techniques needs an electrically conductive material to form the electrodes. Materials used for electrodes must be as conductive as possible to

minimize the electrical resistance and the energy consumption. In the past, the majority of electrodes used were formed from steel. The main problem of using steel as electrodes is corrosion due to electrochemical reactions. Recently, new forms of electrodes based on the use of electrically conductive geosynthetics (EKGs) have been developed, which have the capability of overcoming corrosion.

The concept of EKG is based on combining two established technologies, electrokinetics and geosynthetics. EKG is a new platform technology with applications in agricultural engineering, civil and environmental engineering, waste processing and seabed engineering. It has been identified as a "Show Case" technology by Engineering and Physical Science Research Council (EPSRC).

EKGs are electrically conductive geosynthetics which have enhanced performance over non-conductive geosynthetics. In addition to providing filtration, drainage, separation, reinforcement and acting as membranes, EKGs can be enhanced by electrokinetic techniques for the transport of water and chemical species within fine grained low permeability substrates, which are otherwise difficult or impractical to deal with by conventional methods due to the low hydraulic conductivity of the soils.

EKGs can be of the same basic form as commercially available filter, drainage, separator and reinforcement materials, but offer sufficient electrical conduction to allow the application of electrokinetic techniques. An example of an EKG is illustrated in Figure 2.8. It consists of a metallic conductive core, made of stainless steel wire, coated with conductive carbon polymer. The outer layer of carbon polymer helps to protect the steel from corroding and acts as a conductor itself.

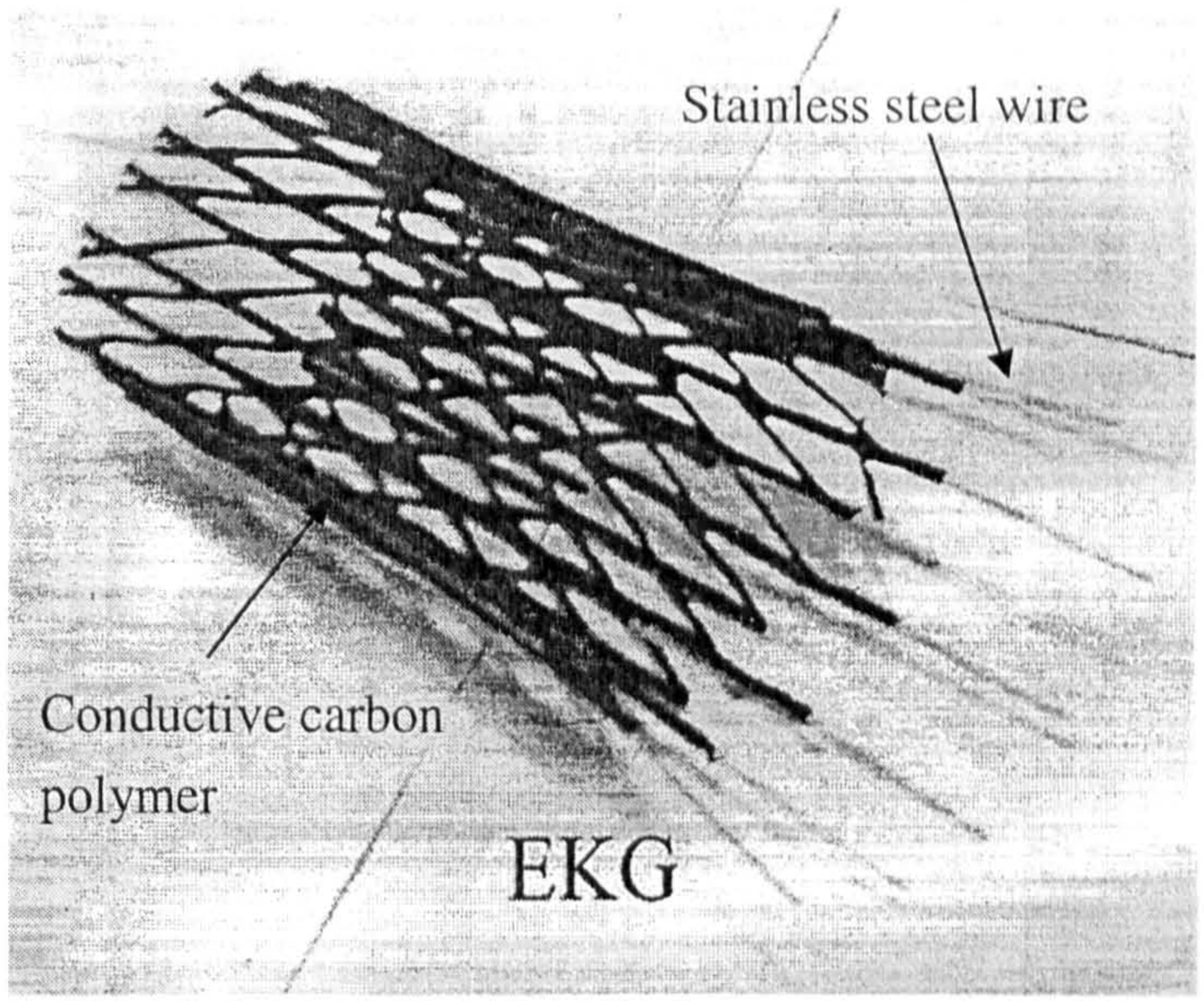


Figure 2.8 Electrokinetic geosynthetic

EKGs have been the subject of research at Newcastle University for a number of years. A range of EKG applications have been identified, including soil consolidation, reinforced soil, soil improvement, waste treatment, sports turf management and sludge dewatering (Jones et al., 1996; Jones and Pugh, 2001; Hamir, 1997; Hamir et al., 2001; Pugh, 2000; Pugh et al., 2000).

2.8.3.1 CONDUCTIVE CARBON POLYMER

Conductive carbon polymer is produced by the addition of conductive carbon black powder to conventional polymers. Conductive carbon black powder is a high structure (long carbon chains) very fine particulate powder formed from the controlled burning of hydrocarbons (Wright and Woodham, 1989). As the concentration of carbon black powder added to the polymer base increases so the electrical conductivity increases until the polymer becomes conductive. In these composites it is the carbon filler which conducts electricity and not the polymer. If carbon black is used as the filler then a minimum loading of between 20% - 30% by weight will be required to produce a suitable conductive polymer (Jones et al., 1996).

When using carbon as the electrodes, carbon oxidises to liberate carbon monoxide and dioxide at the anode, as illustrated in the following reactions:

$$C + 2H_2O \rightarrow CO_2 + 4H^+ + 4e^- \qquad \text{Equation 2.10}$$

$$C + H_2O \rightarrow CO + 2H^+ + 2e^- \qquad \text{Equation 2.11}$$

2.9 HISTORICAL REVIEW OF ELECTROOSMOTIC DEWATERING OF SLUDGE

Many studies on electroosmotic dewatering of sludge have been reported in the literature. A number of these are detailed below:

Barton et al. (1999) demonstrated that at bench scale conventional pressure filtration could be enhanced by the application of an electric field and proved its potential to improve dewatering of difficult materials such as sewage sludge cakes. They produced sludge cakes with solids contents of 35-46wt% using electrokinetically enhanced dewatering, compared with 24-30wt% using pressure filtration alone.

Banerjee and Law (1998) investigated electroosmotic dewatering at both constant voltage and current of two biomass materials, organic humus with peat and composted wastewater sludge. Their investigation showed that electroosmotic dewatering of biomass is feasible both technically and economically. They also found that the flow rate of water out of the sludge at constant voltage increased linearly with the applied electric field and that the electrical energy expended in the constant current dewatering mode was a quadratic function of time.

Chen et al. (1996) studied electroosmotic dewatering of vegetable sludge and mine

tailings and compared the dewatering methods (Pressure, Electroosmotic and combined). Their results showed that a combined field dewatering technique is more effective than electroosmotic dewatering and pressure dewatering for vegetable waste sludge. For mine tailing suspensions, electroosmotic dewatering is as effective as combined field dewatering whereas application of pressure does not give significant enhancement on dewatering.

Gazbar et al. (1994) constructed a laboratory cell which superimposed a mechanical pressure adjustable to 686kPa to the electroosmotic drainage. Their experiments showed that the electroosmotic drainage in the thickening phase enabled domestic sludge to reach very high solids concentration (up to 50.9%) when compared to that of cakes obtained without applying of an electrical field under the same pressure (392kPa).

Gingerich et al. (1999) examined the dewatering of anaerobically and aerobically digested municipal wastewater solids with applied direct pressure and constant voltage direct current simultaneously. They showed that final cake solids could be increased to as much as 50% with the application of 60V DC to wastewater sludge. Their results indicated that dewatering is enhanced through the application of direct pressure coupled with direct current electricity.

Golla et al. (1992) developed an Electro Acoustic Dewatering press, applying a combination of mechanical pressure, electrical current and ultrasonics. The press can remove up to 50% water from filtered sludge cake at a fraction of the cost incurred in thermal drying devices.

Hansen et al. (2001) showed the application of electroosmosis for the drying of four materials. They were chalk sludge, iron hydroxide sludge from waste water cleaning,

deposited fly ash from coal combustion and sludge from an enzyme production rich in biomass. In the electroosmotic experiments, chalk was dewatered from 40 to 79% solids content, iron hydroxide sludge from 2.7 to 19% solids content, fly ash from 75 to 82% solids content and biomass from 3 to 33% solids content.

Heath and Demirel (1984) investigated pressurized electroosmotic dewatering of ultra-fine coal suspensions. They reported that the combination of electric field and pressure increased the dewatering rate compared to dewatering by pressure alone. They also found that electroosmosis could be improved by modifying the zeta potential of the coal suspensions by using chemical additions of potential-determining ions, polyelectrolytes and surfactants.

Kondoh and Hiraoka (1990) reported the successful commercialization of a combined field dewatering process involving the combination of electric field and pressure. By incorporating an electric field as an additional driving force to a pressure dehydrator, the water content of activated sludge could be reduced to 50-60% as compared to 75-85% achieved with pressure alone. The efficiency of the electroosmotic process was ensured by the addition of electrolytes and by the use of specially designed low cost durable carbon electrodes.

Larue et al. (2001) studied the pressurization influence on the electroosmotic dewatering efficiency. They found that increasing the current intensity achieved the maximum cake dryness (in term of cake solid wt%) at minimal specific energy consumption (in terms of kWh/kg of water removed). Their experimental results showed that solids content reached 30wt% at 1A against 22wt% at 0.2A and the energy consumption per kg of water for solids contents was lower for a current intensity of 1A than for a current intensity of 0.5A.

Orsat et al. (1999) studied the effects of combined field dewatering by the simultaneous application of an electrical field and pressure and their individual effects on water removal. They found that the combination of electric field and pressure removed more water than either pressure or electric field alone.

Raats et al. (2002) developed a full-scale electrokinetic dewatering equipment based on a combination of a gravity-driven thickening belt and a belt press, which produced the final dry solids content of drinking water sludge from 17 to 24% by applying an electric potential difference of 30V across the sludge bed, resulting in an additional volume reduction of 15-30%. Without the electrokinetic facility the maximum capacity was limited to 2.0-2.5m^3/h, but with electroosmotic dewatering could be increased to 4m^3/h. Smollen and Kafaar (1994) studied sludge dewatering using a scale model filter-belt in combination with electroosmosis. They found that blinding of the filter media, which is recognised as a major drawback of filtration processes, was markedly reduced by electroosmosis. They also showed that dewatering of anaerobically digested sludges required more energy than that of activated sludges.

Yoshida et al. (1991) studied combined field dewatering involving electroosmotic dewatering and expression with bentonite suspensions, pre-consolidated under a pressure of 98.1kPa. Combined field dewatering enhanced both the dewatering rate and final dewatered volume, compared to the individual processes. The energy consumption for the combined field dewatering process was less than for electroosmotic dewatering alone.

Yoshida (1993) found that the dewatering rate of bentonite sludge by vacuum filtration pressure (80kPa) could be enhanced electroosmotically under the condition of constant voltage of 10V. He also showed that, in the case of electroosmotic dewatering

combined with vacuum dewatering, both the dewatering rate and final dewatered volume were greater than those in the case of electroosmotic dewatering only. His experimental results also suggested that electroosmotic dewatering was not influenced so much by the blocking of the filter medium which was caused by the vacuum filtration pressure.

Yuan and Weng (2002) investigated the effects of processing time and potential gradient (potential difference divided by sample thickness) on water removal by the electrokinetic process and the results showed that increasing either the potential gradient or the processing time would enhance the sludge dewatering efficiency.

Zhou et al. (2001) proposed the dewatering of sludge using a horizontal electric field in order to facilitate the dissipation of gases produced at the electrodes and to keep the anode soaked in water during the dewatering process.

2.10 CHAPTER SUMMARY

The aim of dewatering is to remove as much water as possible from sludge before disposal. Due to the properties of sludge, removal of water cannot easily be carried out by conventional dewatering techniques, which are usually based on the application of mechanical force.

Electroosmosis, which is one of a number of electrokinetic phenomena, is the movement of water under the influence of a direct current electric field. According to the Helmholtz-Smoluchowski theory, electroosmotic flow is a function of voltage gradient and zeta potential and is independent of pore size. Therefore, the electroosmotic dewatering rate is significant when dewatering low hydraulic permeability sludge. Moreover, electroosmotic dewatering can be a low energy

approach. However, electrochemical reactions occur during the dewatering process. Gases are generated at the electrodes and the pH changes near the electrodes. Electrolysis results in reduced dewatering efficiency by changing the zeta potential, which is affected by the pH. The dewatering efficiency can be improved by using combined field dewatering, electrochemical strategies and electrokinetic geosynthetics as electrodes.

In order to simplify the analysis of electrokinetic processes, some assumptions, e.g. constant electroosmotic permeability, no electrochemical reaction, etc., may be made.

In this chapter, conventional dewatering means have been introduced. The concept, theory and application of electroosmosis to dewatering have been briefly discussed. Some of the previous studies into electroosmotic dewatering have also been discussed. It is concluded that electroosmotic dewatering is an efficient method to dewater sludge.

CHAPTER 3

FEASIBILITY ASSESSMENT OF ELECTROOSMOTIC DEWATERING OF SLUDGES

3.1 INTRODUCTION

Everyday wastewater treatment plants product a large quantity of sludge which has to be transported and disposed of. However, the disposal of sludge is extremely expensive due to the high water content of the sludge. Dewatering reduces the water content of the sludge, and reduces the weight of water being transported. Belt filter presses are currently used to dewater sludge before disposal, but this method can only achieve product solids of 15-20 wt%. The implication is that every tonne of dry solids can contain over 6 tonnes of water. In order to reduce disposal costs, a new technology, which can achieve a higher solids content product, is required.

The removal of water within a soil mass by means of an applied electrical potential gradient, electroosmosis, is a recognised process for dewatering of soil and it is postulated that electroosmotic dewatering of sludge can also be applied to enhance the dewatering rate for the purpose of wastewater treatment. This chapter evaluates the feasibility of electroosmotic dewatering of sludges under constant voltage though an experimental programme.

3.2 EXPERIMENTAL PROGRAMME

A number of experiments with different sludge samples were conducted using an electroosmotic cell to determine the electroosmotic dewatering efficiency in terms of dewatering rate, energy consumption and final solid content.

3.2.1 SLUDGE SAMPLES

Four sludge samples, identified as, humic sludge, humic sludge with sawdust, lagoon sewage sludge A and lagoon sewage sludge B were used in the experiment. The average initial solid contents were 16.0%, 24.0%, 15.7% and 9.1% respectively. All sludge samples had the same density of 1.07Mg/m^3.

3.2.1.1 HUMIC SLUDGE

The source of the humic sludge was Esholt sewage treatment works near Bradford, West Yorkshire. This sludge was primary settled and then secondary filtered on large filter beds. The sludge was treated by a belt press with the aid of a small amount of polyelectrolyte flocculant for sludge conditioning.

3.2.1.2 HUMIC SLUDGE WITH SAWDUST

The humic sludge with sawdust was the ex-belt press humic sludge at Esholt mixed with wood waste in the proportion of approximately 40-50% by volume. The addition of wood waste was carried out mainly to improve the mechanical handling characteristics of the sludge. With the sludge/wood waste mixtures, the addition of wood waste increases the shear strength by increasing the internal angle of friction and also reduces the overall moisture content (Lamont-Black and Glendinning, 2004).

3.2.1.3 LAGOON SEWAGE SLUDGES A AND B

Sewage sludges A and B were collected from abandoned lagoons at Rock Farm and Minnworth respectively. Sewage sludge A had a higher proportion of water compared with sewage sludge B, therefore a higher void ratio (proportion of pore space).

3.2.2 ELECTROOSMOTIC CELL

The electroosmotic cell was designed so that combined electrokinetic and pressure

filtration dewatering conditions on samples of sewage sludge could be studied. A schematic of the electroosmotic cell is shown in Figure 3.1. The design was based on the system originally introduced by Banerjee and Vitayasupakorn (1984) and was later modified by Hamir (1997). It consisted of a Perspex cylinder with a fixed plate and an internal movable piston. A small opening in the top of the cell facilitated the escape of water. Porous disc electrodes were located at the top of the piston as well as between the flanges of the cylinder. Lubricant was applied at the internal wall of the cylinder to reduce the friction due to the movement of the piston. The movement of the piston was controlled by compressed air. Conducting wires were connected to the disc electrodes via openings at the top and bottom of the cell. A thin piece of permeable cotton fabric was inserted to separate the sludge from the effluent fluid in order to minimize the loss of sludge sample during filtration.

To eliminate the effect of gravity flow and ensure water was solely removed from the sludge by electroosomsis, the anode was located at the bottom of the cell and the cathode at the top. In this way, electroosmotic flow was generated from the bottom towards the top. The cathode was open to allow drainage and the water retained in a measuring cylinder. The anode was closed so that negative pore water pressure was generated together with consolidation. As the material dewaters, the volume of sludge decreased. In order to avoid separation between the cathode and the top surface of the sludge due to settlement, a pressure was applied to the sludge via the piston which was kept moving upwards and the sludge was always in contact with the electrodes.

3.2.3 POWER SUPPLY

An external power supply was used to provide a potential difference across the sludge sample. The maximum voltage output of the power supply was 30V. The maximum current was 2A, varying depending on the resistance of the sludge sample. If the

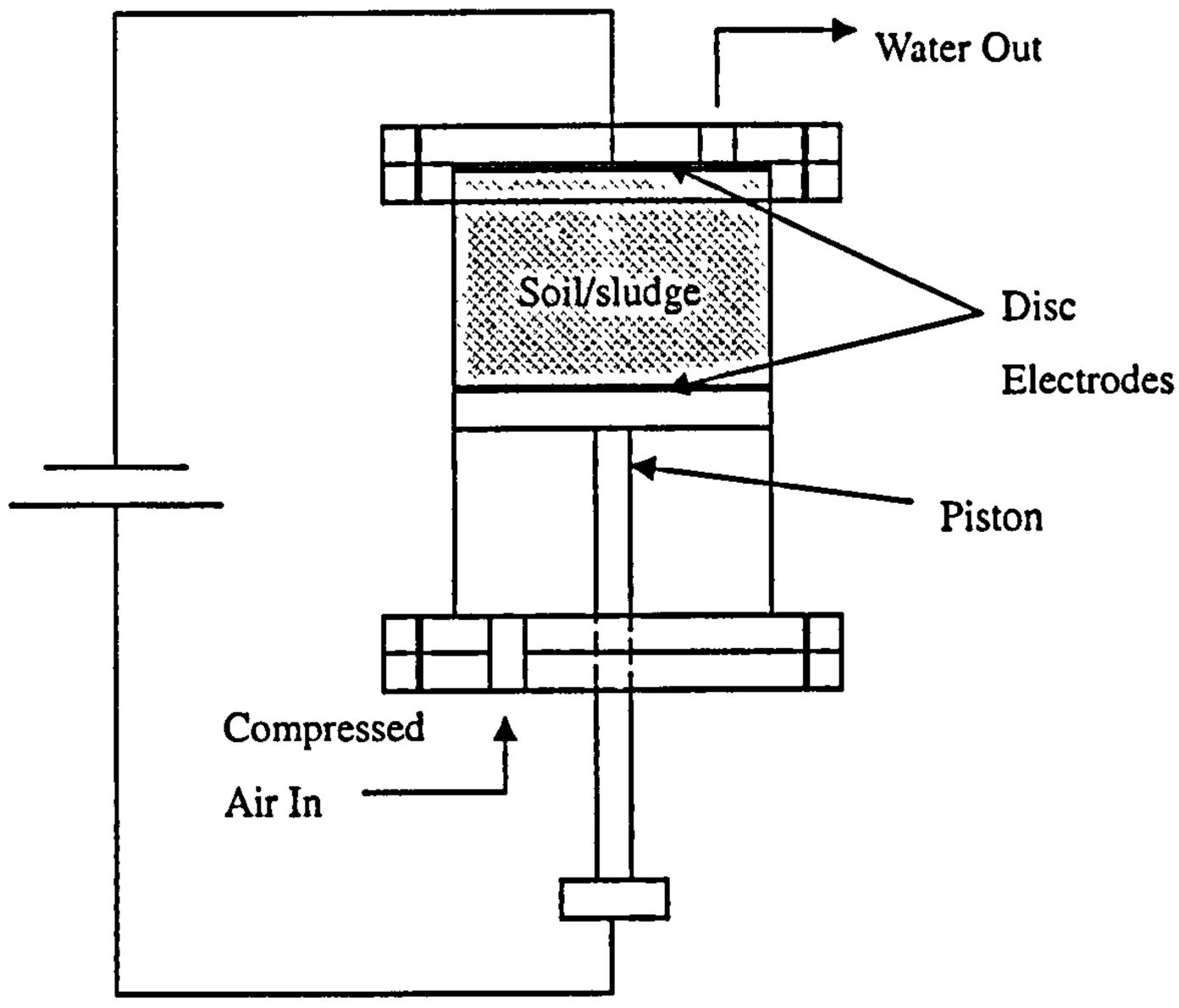


Figure 3.1 Schematic diagram of the electroosmotic cell

current remained constant, the voltage would increase if the resistance of the sludge sample increased. When the voltage reached the maximum of 30V, the current would decrease.

3.2.4 MATERIAL FOR THE ELECTRODES

Copper disks were used as the electrodes. The disks were made of copper plate 1mm thick. Holes of 5mm diameter were punched around the disk to permit drainage and the dissipation of gas.

3.2.5 EXPERIMENTAL TESTING

Initially, the electroosmotic cell was filled with 2234g of sludge, equating approximately to a sample height of 130mm. A constant pressure of 50kPa was applied to the piston. At the same time, an external power supply provided a constant voltage of 13V across the disc electrodes to produce a voltage gradient of 1V/cm. During each test, the current and volume of extracted water were recorded manually every 5 minutes for the first 30 minutes and at intervals of 15 minutes, 30 minutes, 45

minutes and 60 minutes and even several hours thereafter. The power supply was switched off after 72 hours.

A control setup with applied a constant pressure of 50kPa and without electricity was used to compare the results with the final solid content of the treated sludge.

3.3 RESULTS AND DISCUSSION

3.3.1 DEWATERING EFFICIENCY

Figures 3.2 to 3.5 show the graphs of cumulative volume of extracted water against time for humic sludge, humic sludge with sawdust, sewage sludge A and sewage sludge B respectively. It can be seen from the results that, at any time, water removal for all sludge samples with the application of a direct current voltage was more than that in the control (without voltage). The results also show that the cumulative volume of extracted water increased decreasingly with time. In other words, the flow rate decreased with time. This was due to increased electrical resistance. Voltage was drawn by the electrical resistance of the sludge, leading to less voltage available to produce electroosmotic flow. At later stage when electroosmosis was about to cease, application of pressure was the dominant mechanism of extracting water from the cell, rather than that of electricity. Therefore, it can be seen from the results that, at later stage, the cumulative volume of extracted water still increased with time but at a very slow rate.

During the electroosmotic dewatering test, it was observed that, due to large friction generated between the piston and the internal wall of the cylinder, sticking piston occurred and caused unsteady pressure applied to the sludge, resulting non-smooth cumulative volume-time curve and stepped resistance-time curves as shown in Figure 3.2 and Figures 3.12 and 3.13 respectively. Moreover, it can be noticed from Figure

3.4 and 3.5 that there was delay in dewatering for control. This was because the dewatering rate based on application of pressure was very low for sewage sludges A and B that the time for extracted water filling up the void at the top of the cell fully was relatively long.

The total volume of extracted water, final solids and energy consumption for each test after 3 days are summarized in Table 3.1 for each experiment. The results show that a higher final solid content could be obtained and the dewatering rate of sludge could be enhanced by the application of voltage, compared to the results without the application of a voltage (Control). The energy consumption for electroosmotic dewatering varied with different sludge samples ranging between 0.087 and 0.181kWh/kg of extracted water. Compared to 1.2kWh/kg required by thermal drying to evaporate the water, electroosmotic dewatering is less energy consuming and more economic. The overall conclusion is that electroosmotic dewatering of sludge is feasible and potentially economic.

3.3.2 ELECTRIC CURRENT AND RESISTANCE

The electric current reading was found to be maximal at the start of the tests and to decrease with time, as observed in Figures 3.6 to 3.9. Under a constant voltage, the reduction of current was attributed to the increased electrical resistance. Figures 3.10 to 3.13 show the variation of electrical resistance with respect to time for each test. An increase in electrical resistance with time was assumed to be due to electrochemical reactions and desiccation at the anode. During the electroosmotic dewatering process, the water was decomposed and gases were generated at the electrodes, oxygen at the anode and hydrogen at the cathode. Both gases were non-conductive and difficult to remove from the sludge. As a result, resistance increased. On the other hand, water flowed electroosmotically through the sludge from anode to cathode. Therefore, the

water content near the anode dropped rapidly, leading to desiccation and a rise in the electrical resistance of the sludge.

3.3.3 CORROSION

Before the test started, the colour of the copper plate electrodes was fresh reddish brown. After the electroosmotic dewatering process, a thin yellowish-green deposit was found on the surface of the copper electrode at the anode. The occurrence of such a phenomenon, known as corrosion, was attributed to simple or complex electrochemical reactions within the sludge mass. Corrosion was also a reason for an increase in electrical resistance. The formation of the corrosion deposit was probably due to the oxidation reaction taking place at the copper anode. No corrosion deposit was seen on the surface of the cathode. This confirms that corrosion is more likely to occur in anode electrodes and that preventive measures are required to reduce this phenomenon.

3.3.4 VOLTAGE GRADIENT

Under a constant voltage supply, the voltage from the power supply was the sum of voltage drawn to generate electroosmotic flow and voltage drawn by resistance due to electrochemical reactions and desiccation. From the results in Section 3.3.2, it is seen that the electrical resistance increased rapidly as the treatment time became longer. Therefore, the voltage available to generate electroosmotic flow became less. Once the resistance reached a critical value at which the flow rate with application of electricity was equal to the flow rate of the control (both curves are parallel as shown in Figure 3.5 at later stage), electroosmotic flow ceased virtually.

As the voltage drawn for electroosmotic flow decreases with time under a constant voltage supply, it is argued that a constant voltage from the power supply applied to the sludge is not equivalent to a constant voltage gradient applied to the sludge. When

designing an electroosmtoic dewatering system under constant voltage, the Helmholtz-Smoluchowski equation (see Section 2.6.3.1) is usually applied with the assumptions of no electrochemical reaction and constant electroosmotic flow rate to simplify the analysis process. However, this simplified design cannot predict the dewatering process accurately as in practice the voltage gradient to generate electroosmotic flow decreases with time. Therefore, it is necessary to develop a more accurate framework for the design of electroosmotic sludge dewatering.

3.4 CHAPTER SUMMARY

In order to lower the cost of transportation and disposal of sludge, it is desirable to reduce the water content as much as economically possible. Dewatering based solely on the application of compression is not efficient. Recently, it has been found that combining electroosmotic dewatering with compression is an efficient technique.

This chapter evaluates the feasibility of electroosmotic dewatering of sludge and examines its efficiency through a number of experiments. The experimental results show that higher final solid contents could be obtained and the dewatering rate of sludge could be enhanced by the application of electricity, compared to the application of compression alone. The energy consumption for electroosmotic dewatering of sludge was found to be economic, compared to thermal drying. It is concluded that electroosmotic dewatering of sludge is both feasible and potentially economic.

The experimental results also show that electrical resistance increased and current decreased with time during the dewatering process with a constant applied voltage. Increased resistance, which was mainly caused by electrochemical reactions and desiccation, affected the voltage drawn to generate electroosmotic flow so that the electroosmotic flow rate decreased with time. Therefore, the voltage gradient applied

to the sludge to generate the electroosmotic flow is not constant and decreases with time even though a constant voltage from a power supply is applied to the sludge.

As the electroosmotic flow rate varied with time, the use of the Helmholtz-Smoluchowski flow equation together with the assumptions of no electrochemical reaction and a constant electroosmotic permeability to predict the dewatering process is not accurate. Development of a more accurate design framework for electroosmotic dewatering of sludge is therefore necessary and is the subject of next chapter.

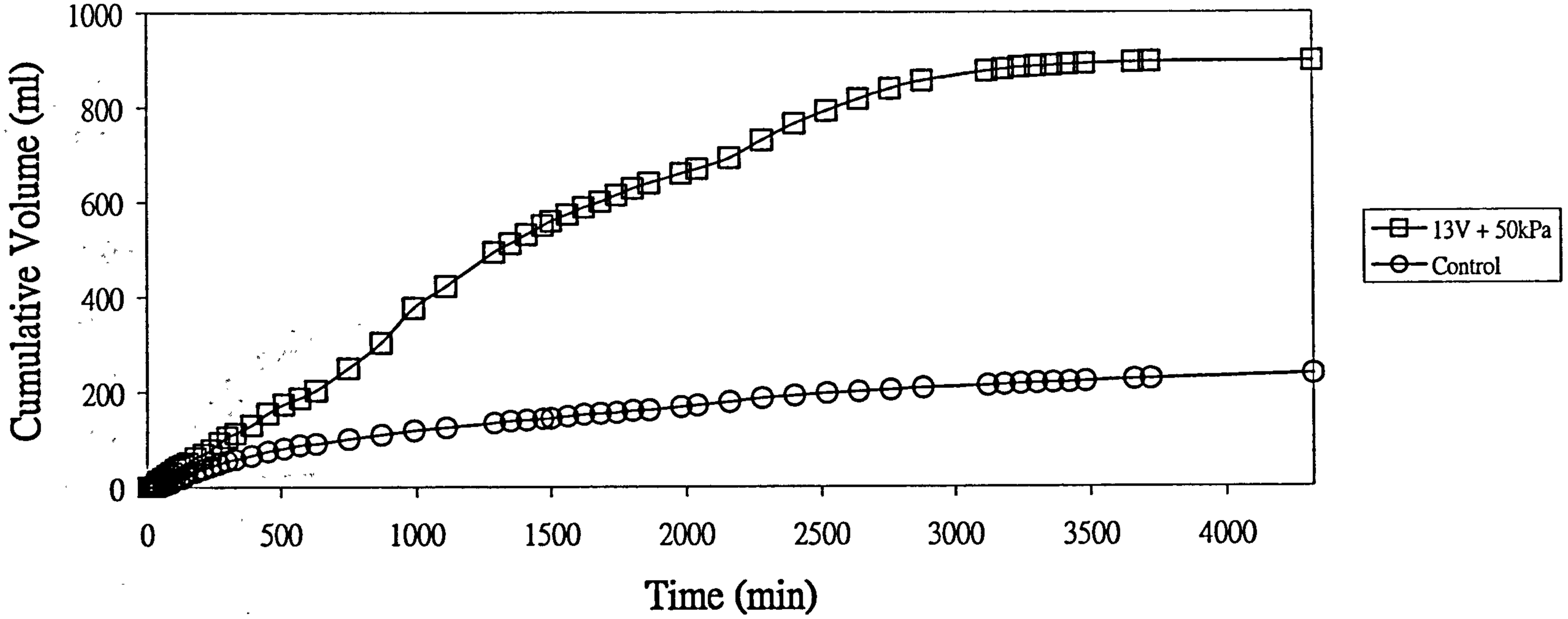


Figure 3.2 Cumulative volume of extracted water against time for 2234g humic sludge at 16.0% initial dry solid content

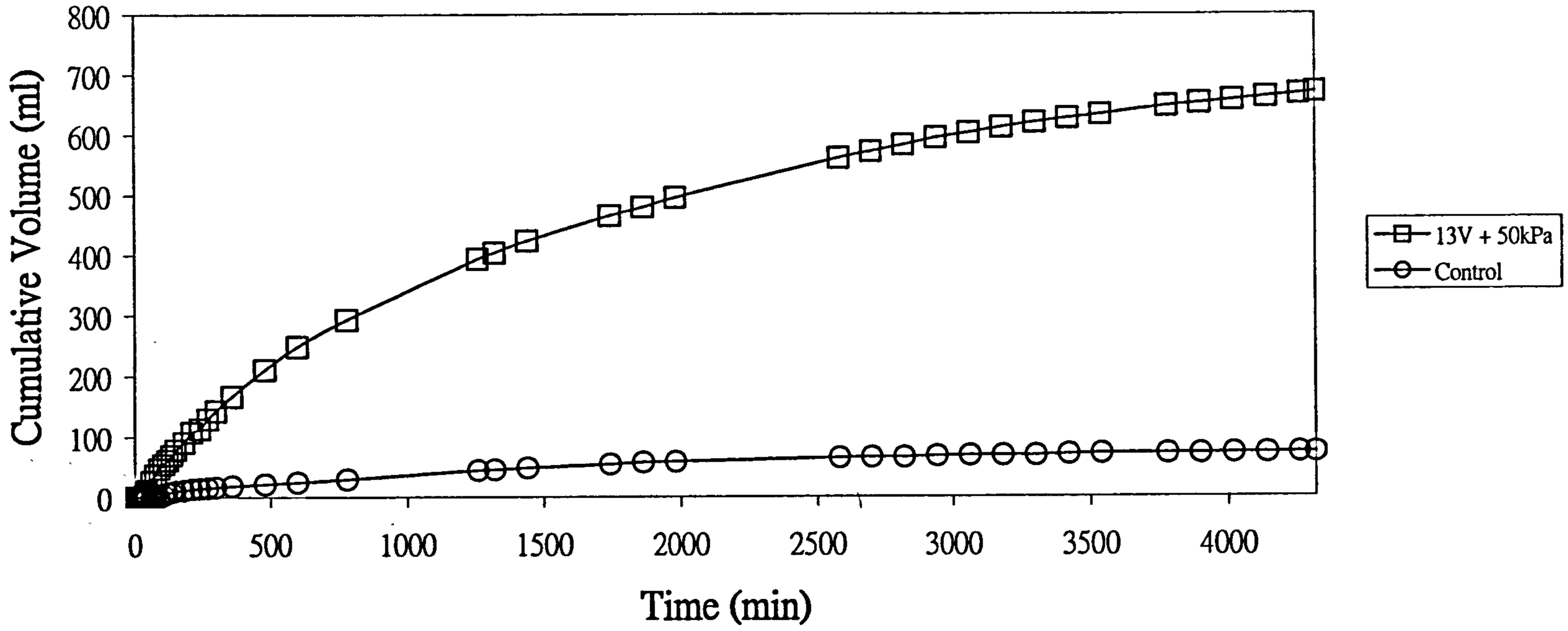


Figure 3.3 Cumulative volume of extracted water against time for 2234g humic sludge with sawdust at initial 24.0% dry solid content

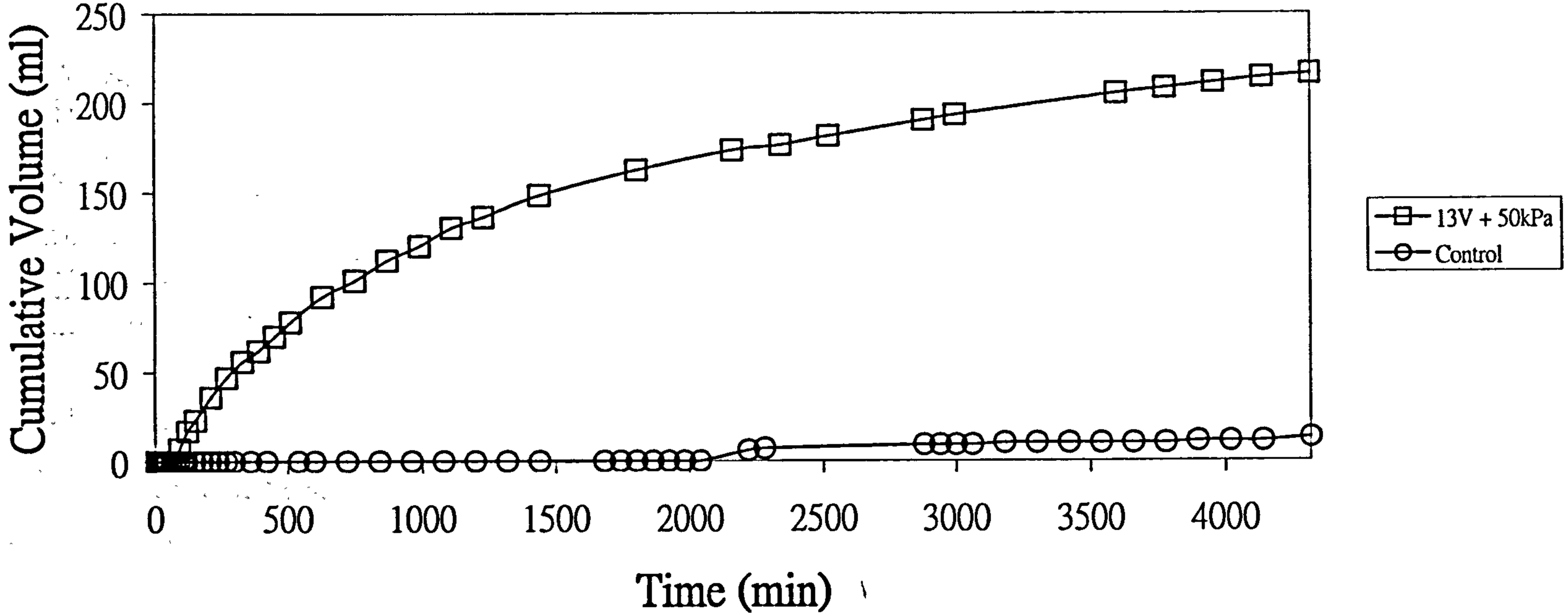


Figure 3.4 Cumulative volume of extracted water against time for 2234g sewage sludge A at initial 15.7% dry solid content

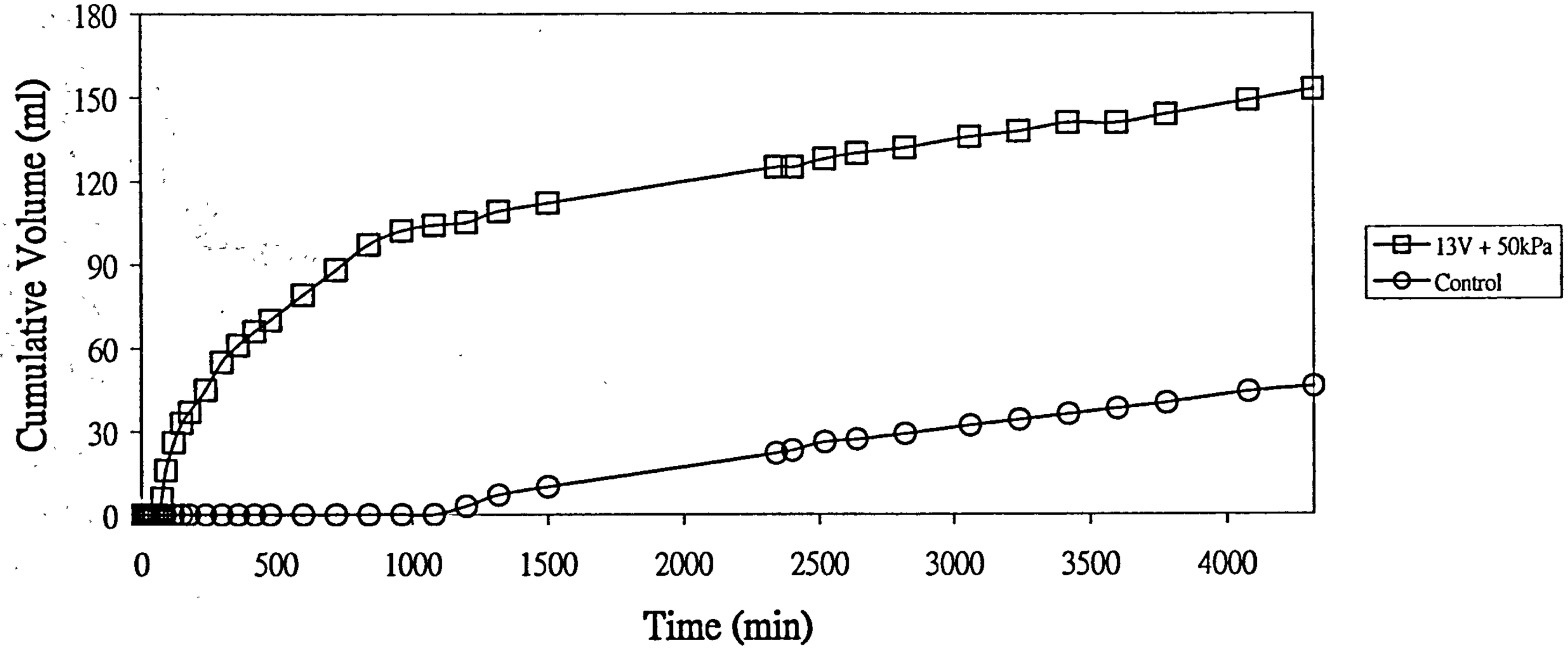


Figure 3.5 Cumulative volume of extracted water against time for 2234g sewage sludge B at 9.1% initial dry solid content

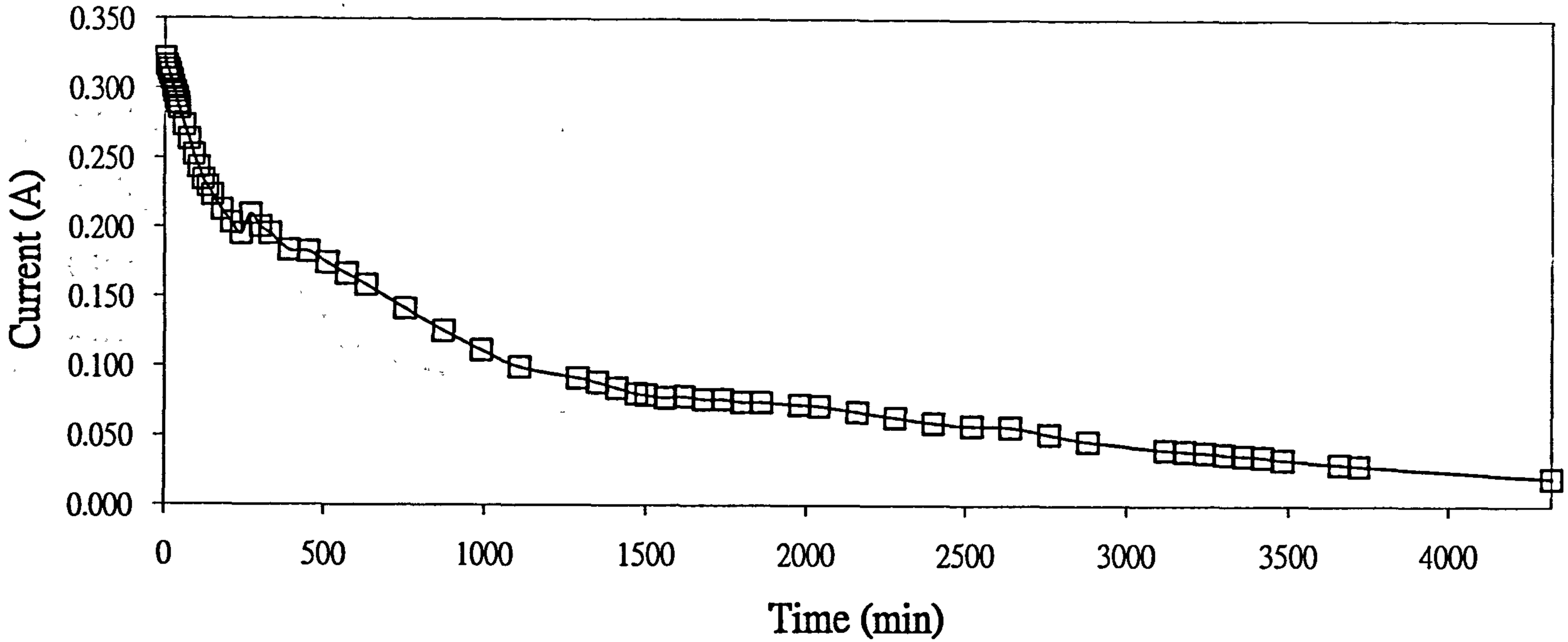


Figure 3.6 Current against time for 2234g humic sludge at 16.0% initial dry solid content

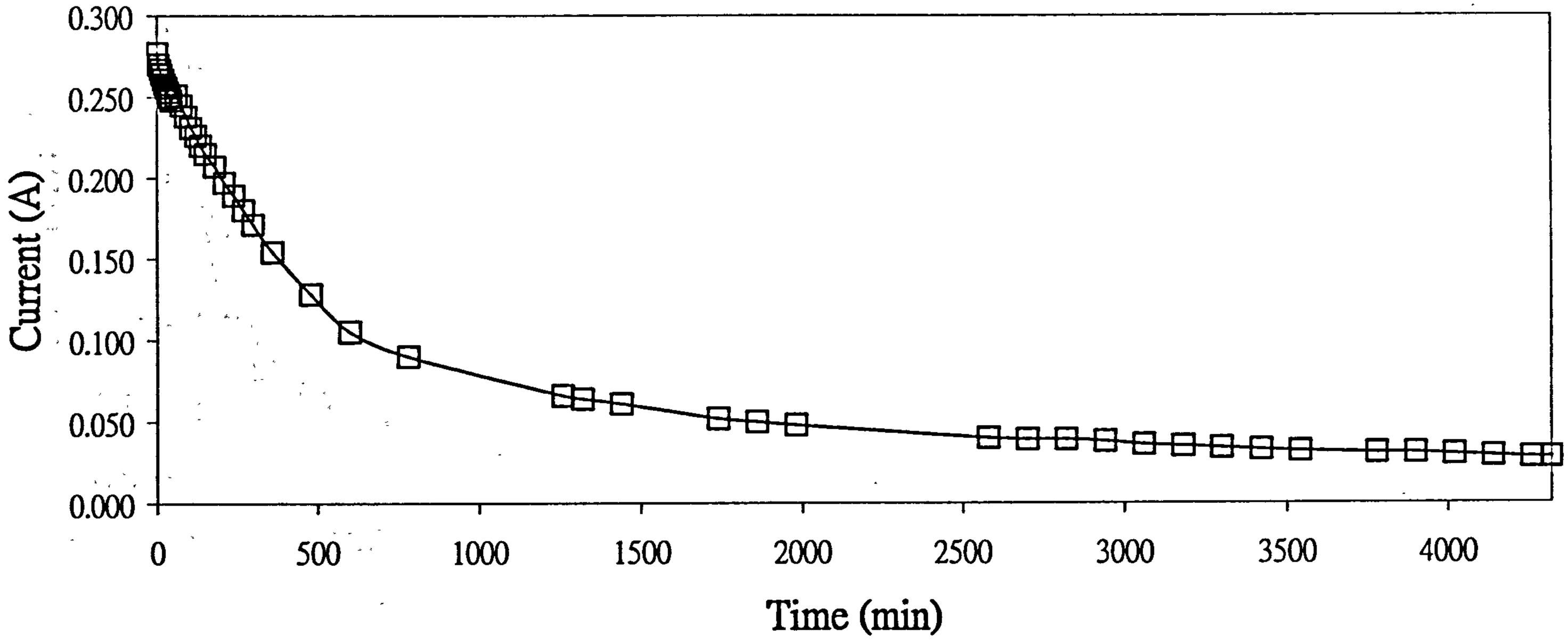


Figure 3.7 Current against time for 2234g humic sludge with sawdust at 24.0% initial dry solid content

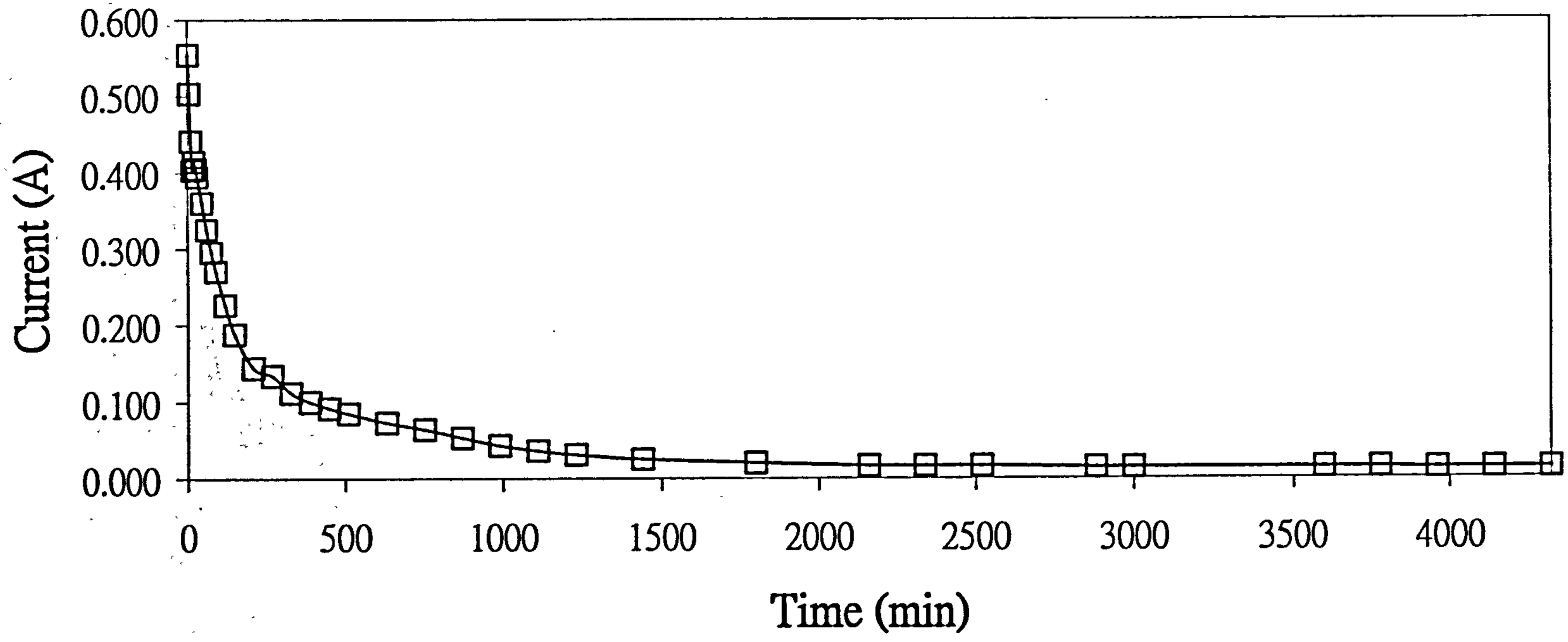


Figure 3.8 Current against time for 2234g sewage sludge A at 15.7% initial dry solid content

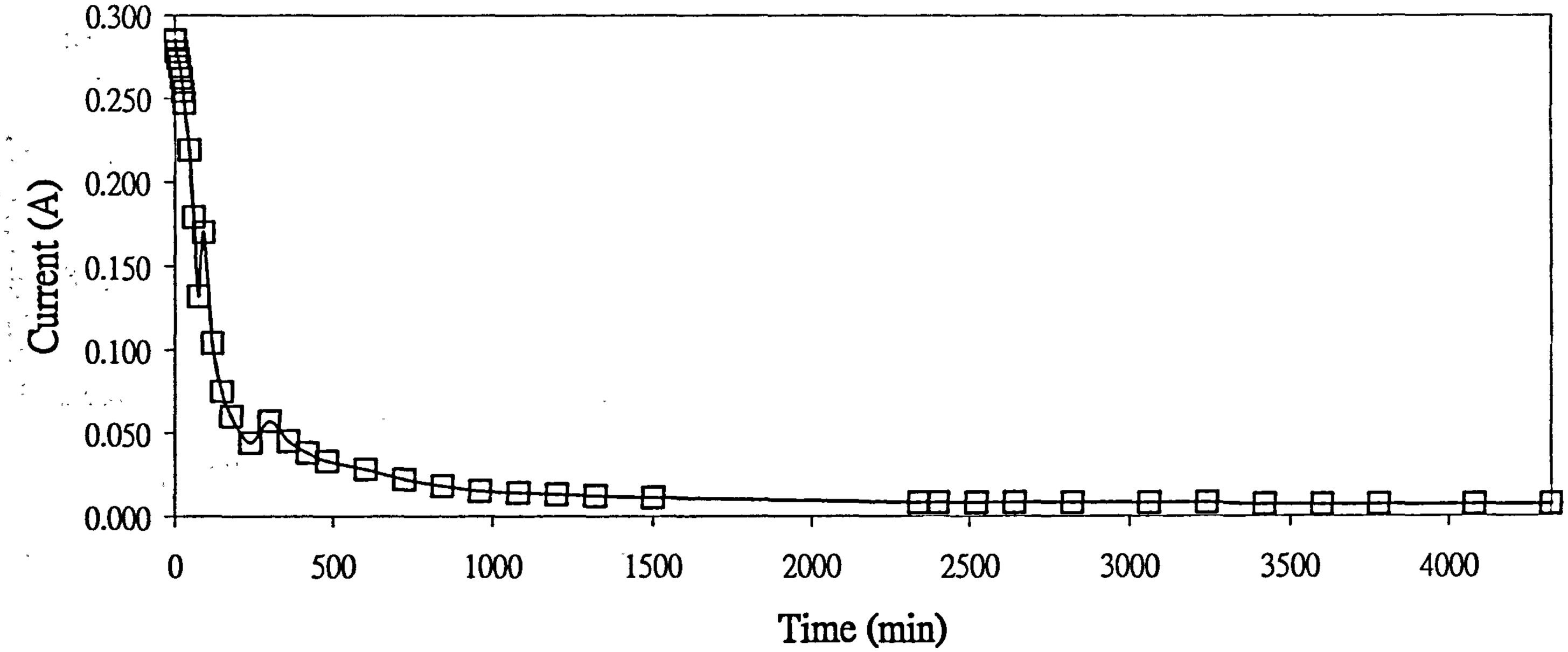


Figure 3.9 Current against time for 2234g sewage sludge B at 9.1% initial dry solid content

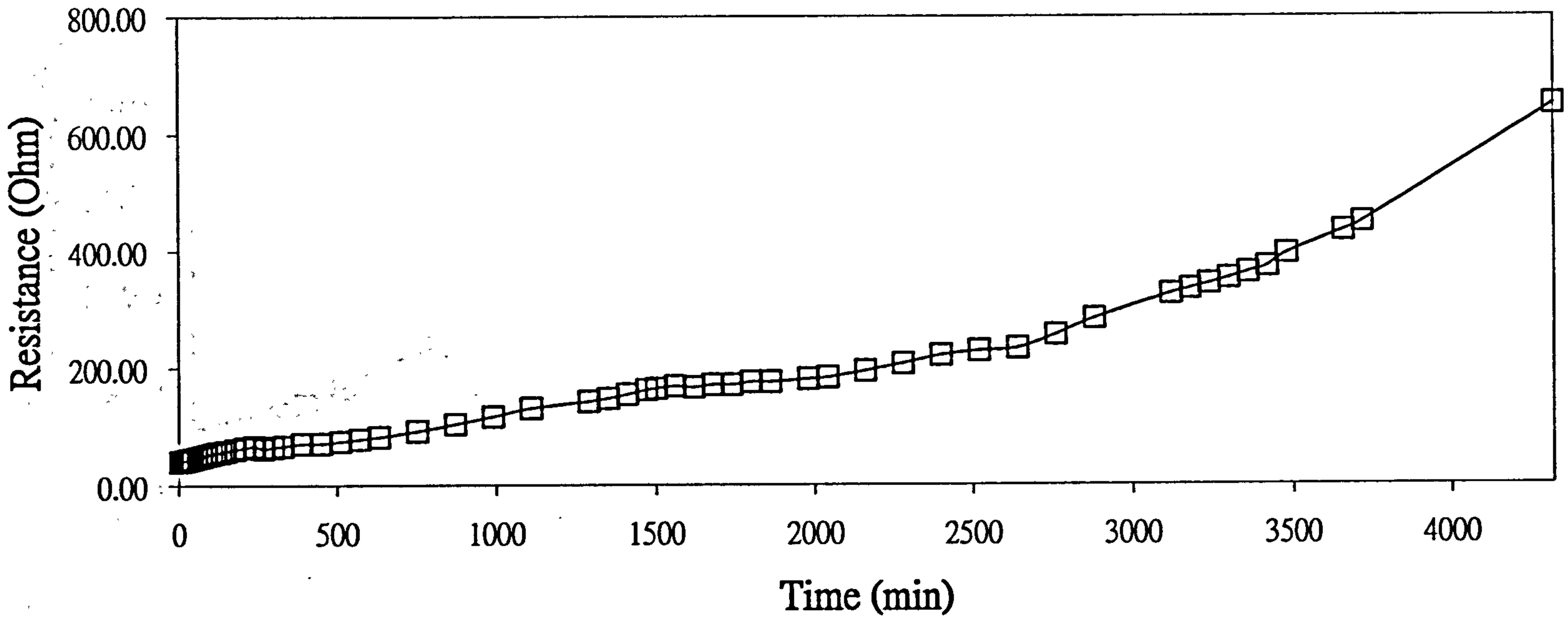


Figure 3.10 Resistance against time for 2234g humic sludge at 16.0% initial dry solid content

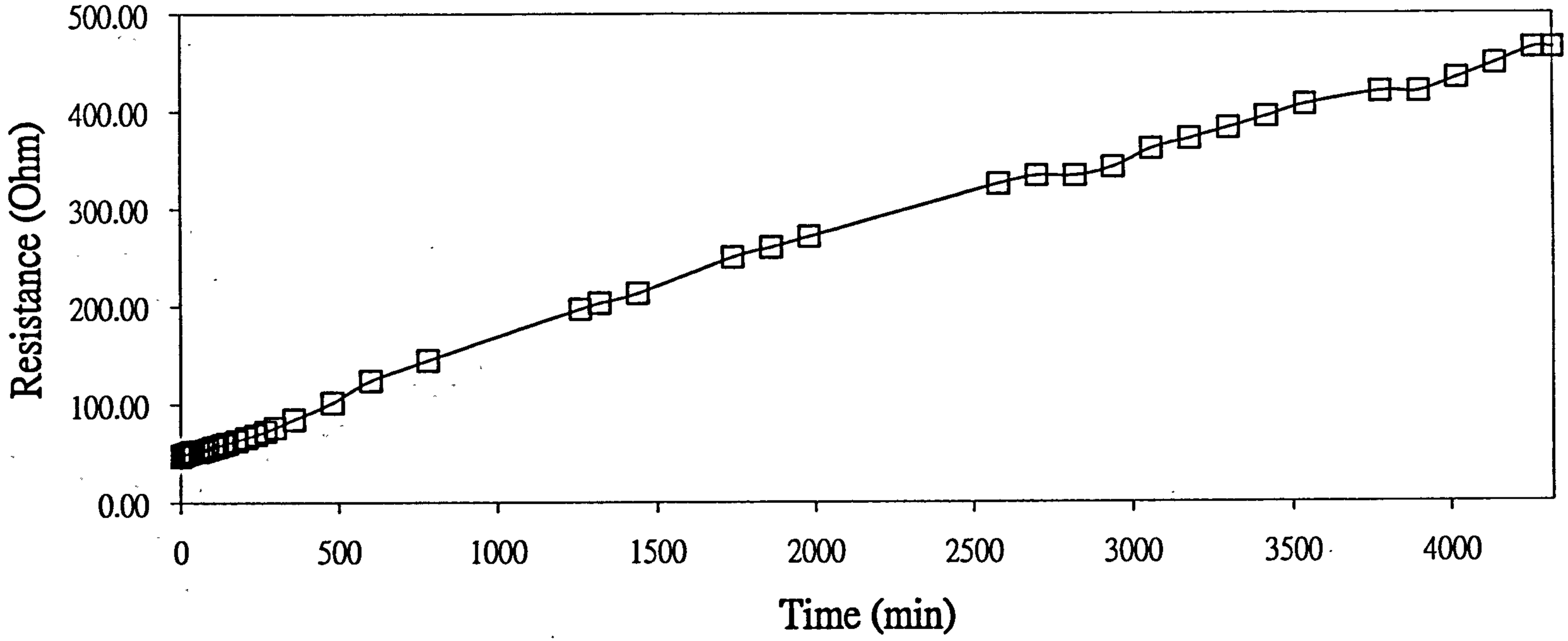


Figure 3.11 Resistance against time for 2234g humic sludge with sawdust at 24.0% initial dry solid content

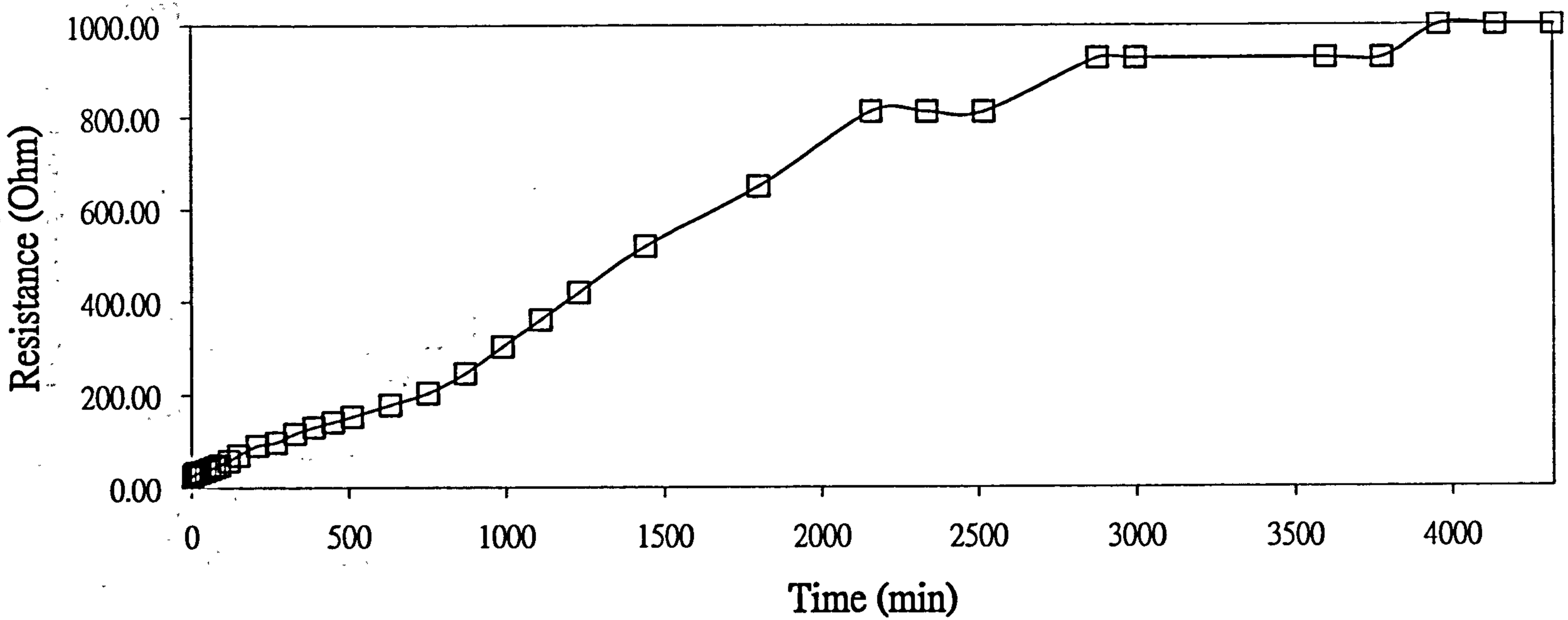


Figure 3.12 Resistance against time for 2234g sewage sludge A at 15.7% initial dry solid content

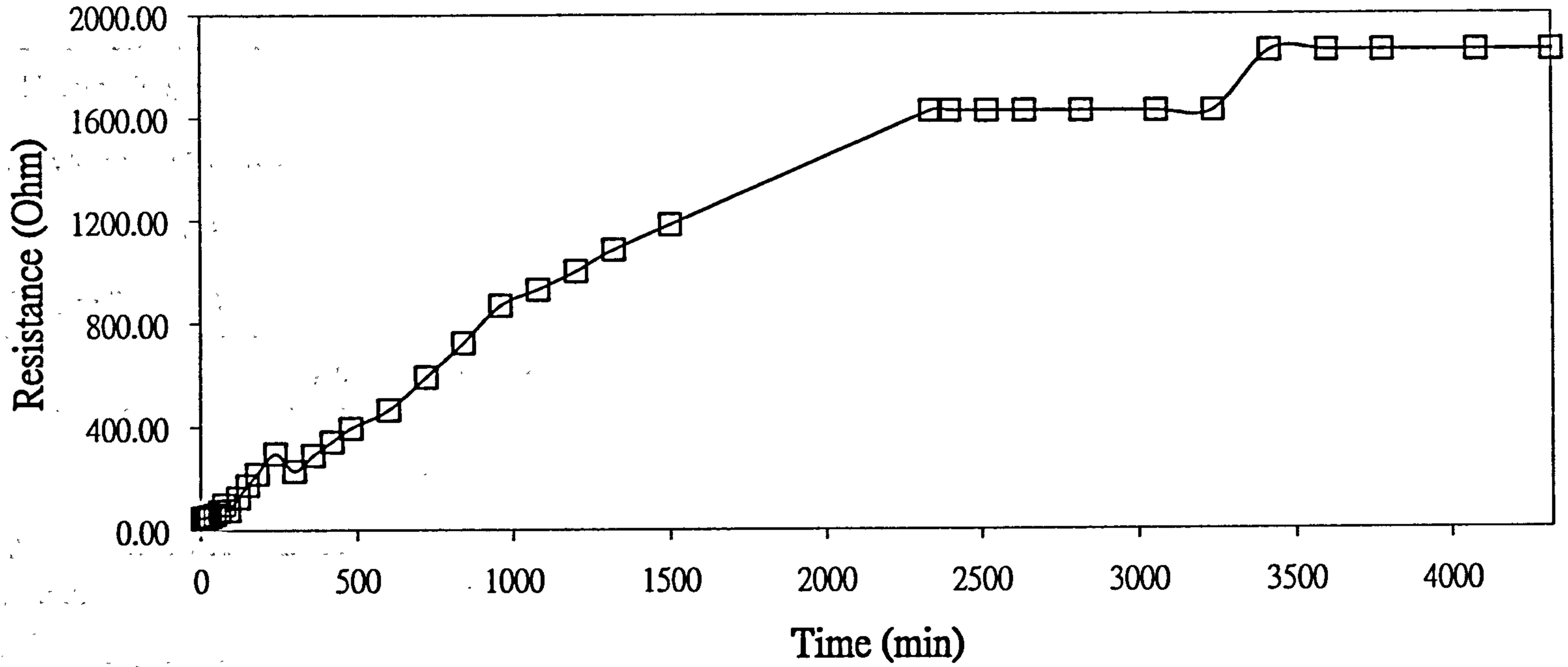


Figure 3.13 Resistance against time for 2234g sewage sludge B at 9.1% initial dry solid content

Table 3.1 Experimental results: Cumulative volume of extracted water, final solids and energy consumption after 3 days

Electroosmotic Dewatering with 13V and 50kPa				
Sludge	Total Volume of Extracted Water (ml)	Initial Solids (%)	Final Solids (%)	Energy Consumption (kWh/kg of extracted water)
Humic Sludge	897	16.0	26.7	0.087
Humic Sludge with Sawdust	670	24.0	34.3	0.093
Sewage Sludge A	216	15.7	17.4	0.181
Sewage Sludge B	153	9.1	9.8	0.117

Electroosmotic Dewatering with 50kPa and without Electricity (Control)				
Sludge	Total Volume of Extracted Water (ml)	Initial Solids (%)	Final Solids (%)	Energy Consumption (kWh/kg of extracted water)
Humic Sludge	237	16.0	17.9	-
Humic Sludge with Sawdust	73	24.0	24.8	-
Sewage Sludge A	13	15.7	15.8	-
Sewage Sludge B	46	9.1	9.3	-

CHAPTER 4

INTEGRATING FRAMEWORK FOR THE DESIGN OF ELECTROOSMOTIC DEWATERING OF SLUDGE

4.1 INTRODUCTION

Electroosmotic dewatering has been shown to be an effective method of dewatering sludge. However, this method has not been commonly used in practice. This is because the effectiveness of the electroosmotic dewatering process is affected by the variation of the treatment variables and there is no design equation which enables one to predict the dewatering process accurately.

In Chapter 3, it was shown that electroosmotic flow rate decreased and electric resistance increased with time due to electrochemical reactions when dewatering with constant voltage. Therefore, the use of the Helmholtz-Smoluchowski flow equation together with the assumptions of no electrochemical reaction and a constant electroosmotic permeability is not applicable for the design of an electroosmotic dewatering system with constant voltage.

In order to predict the dewatering process accurately, development of a more accurate design framework is required. This chapter presents an integrating framework for the design of electrokinetically enhanced dewatering of sludge and demonstrates its applicability through an experimental programme.

4.2. EXISTING EQUATION FOR ELECTROOSMOTIC DEWATERING

When a current is applied to saturated fine-grained soils, the electro-potential developed between the electrodes causes water to flow from the anode to the cathode through the soil mass by electroosmosis. The Helmholtz-Smoluchowski theory is the earliest and most widely used (Mitchell 1991) to describe this phenomena.

It states that the electroosmotic flow of water through a fine-grained material can be written as:

$$Q_e = k_e i_e A \qquad \text{Equation 4.1}$$

where Q_e is the electroosmotic flow rate, i_e is the potential gradient $\Delta V/\Delta L$ (where V is voltage and L is distance), A is the cross-sectional area and k_e is the coefficient of electroosmotic permeability.

This is very similar in form to Darcy's equation for hydraulic flow through a soil:

$$Q_h = k_h i_h A \qquad \text{Equation 4.2}$$

where Q_h is the water flow rate, i_h is the hydraulic gradient $\Delta H/\Delta L$ (where H is hydraulic head), A is the cross-sectional area and k_h is the hydraulic permeability of the soil.

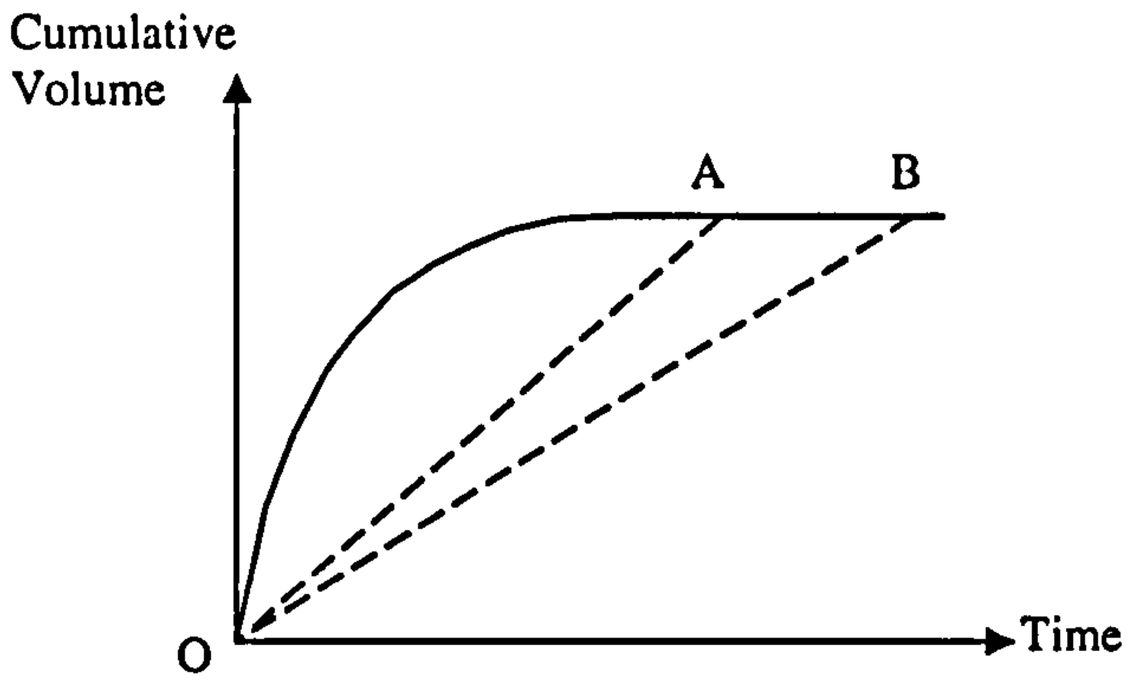


Figure 4.1 Typical experimental result of electroosmotic dewatering

There is a fundamental difference in the two permeabilities, k_e and k_h; whereas k_e is independent of the size of the individual pores and k_h is very strongly influenced by the pore size (Casagrande 1949).

In order to simplify the analysis of the electroosmotic dewatering process, the electroosmotic permeability is assumed to be a constant in most mathematical models, as mentioned in Section 2.6.5. Using the equation for electroosmotic flow (Equation 4.1), if the electroosmotic permeability is assumed to be a constant, then the graph for the cumulative volume of extracted water should be linear and proportional to the applied voltage when the cross-sectional area and the voltage gradient are maintained at a constant.

However, in reality, the electroosmotic permeability decreases with increasing treatment time and the electroosmotic flow rate slows down due to electrochemical reaction and desiccation at the anode (positive electrode) causing an increase in resistance. Figure 4.1 shows a typical graph of cumulative volume of collected water against time plotted from experimental data for a sample of constant cross-sectional area with a constant potential gradient. The slopes of OA and OB represent the flow rate calculated at times

A and B after the start of treatment. The coefficient of electroosmotic permeability decreases with time as the flow rate decreases with time (i.e. gradient OA > gradient OB). Therefore, the assumption that electroosmotic permeability is constant for design cannot be valid because a constant flow rate cannot be obtained in practice. The factors affecting the electroosmotic dewatering process, resulting from a change of resistance in a closed circuit are briefly summarised in Table 4.1 and demonstrate that many factors have to be considered during the design process. Therefore, further refinement of the Helmholtz-Smoluchowski equation with coefficients to account for each of these factors to produce a design framework is fraught with difficulty.

4.3 DERIVING NEW EQUATIONS FOR ELECTROOSMOTIC DEWATERING

The equations presented herein are based upon modelling the entire dewatering system as an electric circuit and using the supporting mathematics to produce an integrating framework for design.

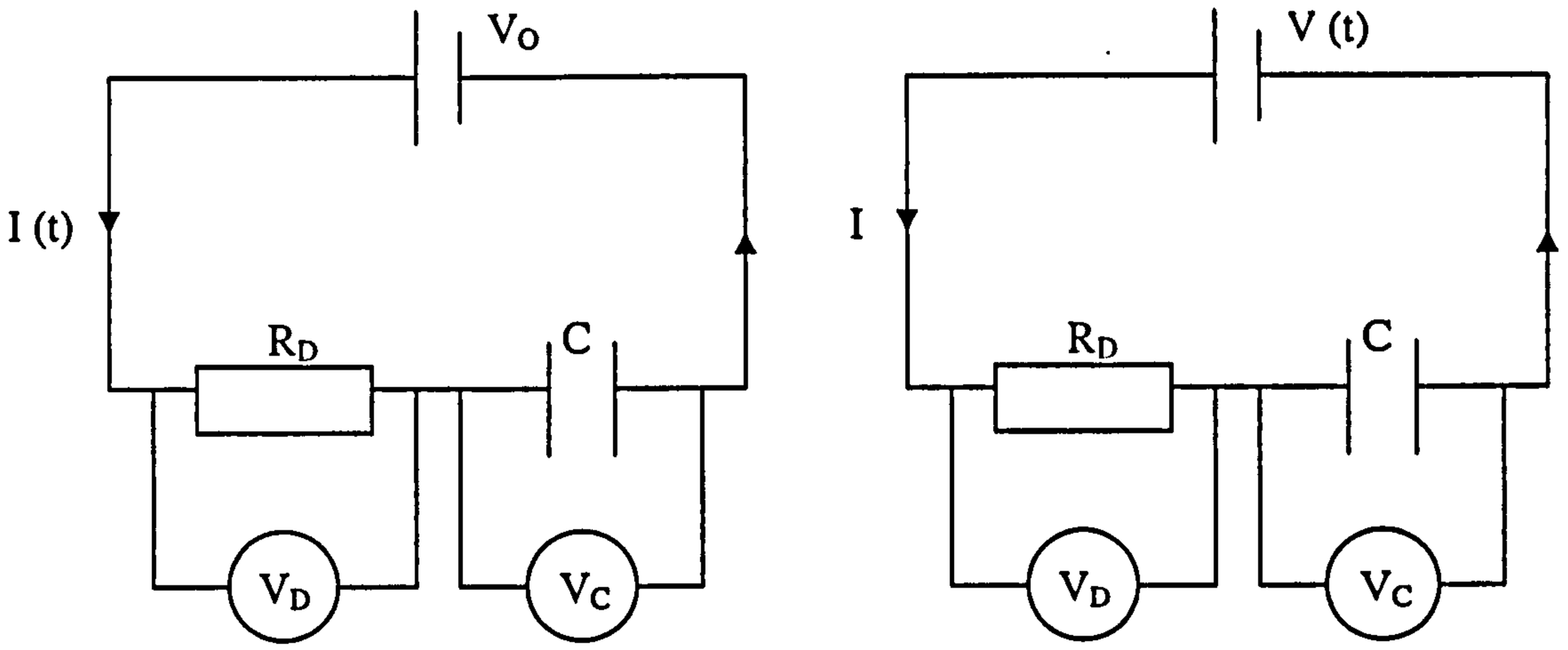
4.3.1 ASSUMPTIONS OF ELECTROOSMOTIC DEWATERING

The model of electroosmotic dewatering is based on the following assumptions:

1. The sludge is homogeneous and fully saturated;
2. There is no movement of particles by electrophoretic migration;
3. The water in the sludge moves electroosmotically in the one-dimensional direction between electrodes;
4. The electroosmotic permeability, k_e, is constant with time;
5. No electrochemical reactions occur during electroosmotic dewatering;
6. Darcy's law and Ohm's law are applicable during electroosmotic dewatering.

Table 4.1 Factors affecting electroosmotic dewatering process

Factors	Description
Soil electric conductivity	When soil electrical conductivity increases, the efficiency decreases as currents bypass the pore medium.
Pore fluid electric conductivity	Efficiency increases as pore fluid electrical conductivity increases.
Moisture content	Efficiency depends on moisture content. The electrokinetic process will eventually shut down when no water is supplied continuously at the anode.
Conducting minerals	If electrical conductivity of the solids is high, the efficiency will decrease.
Electric field density	Increasing electric field density increases the electroosmotic flow rate.
Current density	High current will generate more acid and increase the transport rate of ions but is expensive in terms of current used.
pH	During electrokinetic process, pH is low at the anode due to H^+ generated by electrolysis and the pH is high at the cathode due to OH^-. The efficiency is significantly dependent on the pH value. When treated sludge reaches a steady state at the end of the process, it is acidic. Low pH will affect the zeta potential from negative to positive so that the electroosmotic flow may reverse.
Zeta potential	The electroosmotic flow rate increases with a higher zeta potential (more negative). It is affected by pH.
Ionic strength	If ionic strength of pore water is too strong, it will reduce the zeta potential so that electroosmotic flow rate decreases.



(b) Electroosmotic dewatering with constant voltage

(a) Electroosmotic dewatering with constant current

Figure 4.2 Schematic closed circuits of electroosmotic dewatering process with constant voltage and constant current

4.3.2 MODELLING THE DEWATERING SYSTEM AS AN ELECTRIC CIRCUIT

In the electroosmotic dewatering system shown in Figure 3.1, two conducting electrode plates connected across a voltage source are placed around the layer of sludge. In physics, this would be regarded as an electric circuit connecting a capacitor. A capacitor consists of two conducting plates separated by an insulating layer called a dielectric. When a capacitor is connected in a circuit across a voltage source, the voltage forces electrons onto the surface of one plate and pulls electrons off the surface of the other plate resulting in a potential difference between the plates. In the case of electroosmotic dewatering, the sludge acts as the insulating layer separating two conducting electrodes. Using this analogy, electroosmotic dewatering may be regarded as the process of charging a capacitor.

An electroosmotic dewatering system can be considered as having three elements in series, a power supply (V_O), a capacitor (C) and a constant resistance (R_D) (see Figure 4.2). R_D on its own represents the process of dewatering sludge with constant k_e and

without any electrochemical reaction effect. The potential difference across the constant resistance R_D (V_D) is the potential difference needed to generate the electroosmotic flow. The potential difference across the capacitor C (Vc) varies with time and represents the variation in k_e with time brought about by electrochemical effects. At time = 0, the potential difference across the capacitor C (Vc) is assumed to be zero and to increase with time. When time tends to infinity, the potential difference across the capacitor C (Vc) is assumed to be V_O and the potential difference across the constant resistance R_D (V_D) is zero. At that time, current will cease to flow. That means there is no voltage across the dewatering device at time = ∞ provided that electroosmotic flow has ceased.

There are two potential options for the control of electroosmotic dewatering: constant voltage with variable current or constant current with variable voltage. Both approaches will be discussed further herein.

4.3.3 ELECTROOSMOTIC DEWATERING WITH CONSTANT VOLTAGE

In Figure 4.2a, a capacitor C is connected in series with a constant resistance R_D to a power supply of constant voltage V_O. In this case, voltages across R_D (V_D) and C (V_C), and current (I) are function of time.

The capacitance C of a capacitor is defined as the charge (Q) stored per unit voltage (V) applied across it. Mathematically, capacitance is defined as

$$C = Q / V \qquad \text{Equation 4.3}$$

Current I is defined as the movement of charge (Q) per unit time (t). Mathematically, current is defined as

$$I = Q / t \qquad \text{Equation 4.4}$$

When the power supply is switched on, the initial current I_O is independent of C whose potential difference is zero. Thus,

$$I_O = V_O / R_D \qquad \text{Equation 4.5}$$

Because the current I decreases with time, the potential difference across R_D can be written as

$$V_D = I(t)R_D \qquad \text{Equation 4.6}$$

The potential difference across C is

$$V_C = Q / C \qquad \text{Equation 4.7}$$

and

$$\frac{dV_C}{dt} = \frac{I(t)}{C} \qquad \text{Equation 4.8}$$

At any instant, the voltage from the power supply V_O is the sum of V_D and V_C. Thus,

$$V_O = V_D + V_C$$ Equation 4.9

and

$$\frac{dV_O}{dt} = \frac{dV_D}{dt} + \frac{dV_C}{dt}$$ Equation 4.10

Substituting from Equation 4.6 and Equation 4.8,

$$0 = R_D \frac{dI(t)}{dt} + \frac{I(t)}{C}$$ Equation 4.11

By first order non-homogenous differential equation,

$$a\frac{df(x)}{dx} + bf(x) + c = 0$$ Equation 4.12

$$f(x) = Be^{\frac{-bx}{a}} + \frac{c}{b}\left[e^{\frac{-bx}{a}} - 1\right]$$ Equation 4.13

where $f(x) = B$ at $x = 0$

Therefore,

$$I(t) = \frac{V_O}{R_D} e^{\frac{-t}{R_D C}}$$ Equation 4.14

Substituting from Equation 4.5, the current I is

$$I(t) = I_O e^{\frac{-t}{R_D C}}$$ Equation 4.15

Substituting Equation 4.15 into Equation 4.6, the potential difference across R_D is

$$V_D(t) = R_D I_O e^{\frac{-t}{R_D C}}$$ Equation 4.16

Substituting Equation 4.16 into Equation 4.9, the potential difference across the capacitor C is

$$V_C(t) = V_O(1 - e^{\frac{-t}{R_D C}})$$ Equation 4.17

R_D represents the process of dewatering sludge with constant k_e and without electrochemical reaction effect. The voltage across R_D (V_D) is the potential difference ΔV applied to the sludge. It can be seen from the Equation 4.16 that the voltage across the constant resistance R_D (V_D) is a function of time and decreases exponentially. Therefore, the potential gradient ($\Delta V/\Delta L$) is also a function of time and decreases exponentially. The cumulative volume of collected water by electroosmosis is given by:

$$Vol(t) = \int_0^t k_e A \frac{V_D(t)}{L} dt$$ Equation 4.18

Substituting Equation 4.16 into Equation 4.18,

$$Vol(t) = \frac{k_e A R_D I_O}{L} \int_0^t e^{\frac{-t}{R_D C}} dt$$ Equation 4.19

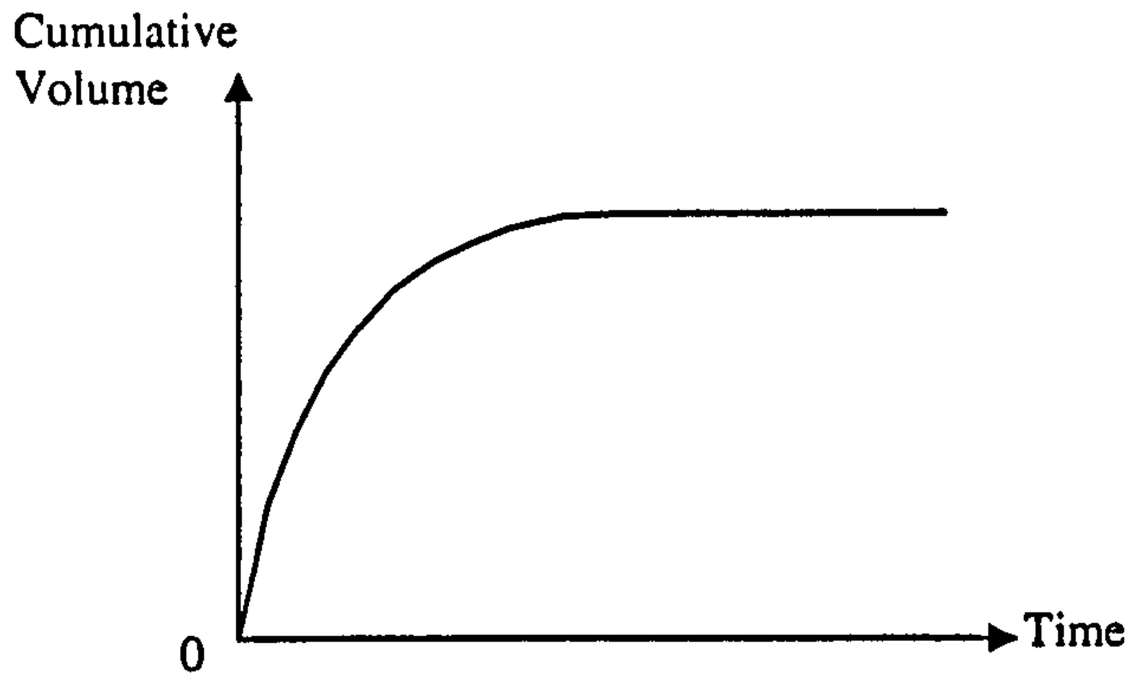


Figure 4.3 The relationship between cumulative volume and time when a sludge is dewatered with constant voltage

$$Vol(t) = \frac{k_e A V_O}{L}(1 - e^{\frac{-t}{R_D C}}) \qquad \text{Equation 4.20}$$

Equation 4.20 shows that the electroosmotic flow rate decreases with time even through the coefficient of electroosmotic permeability is assumed to be a constant. According to Equation 4.20, the relationship between the cumulative volume and time is represented in Figure 4.3. Based on the analogy of charging a capacitor with constant voltage, a decrease in the electroosmotic flow rate with time can be explained by Equation 4.20 when a constant electroosmotic permeability is still assumed. This cannot be explained by Helmholtz-Smoluchowski equation (Equation 4.1).

4.3.4 ELECTROOSMOTIC DEWATERING WITH CONSTANT CURRENT

The condition of constant current is now examined. It is modelled by the circuit shown in Figure 4.2b. In order to retain constant current, the voltage from the power supply has to increase. In this case, the variation in the voltage from the power supply is a function of time whereas the potential difference across R_D (V_D) is kept constant as

$$V_D = IR_D \qquad \text{Equation 4.21}$$

When the power supply is switched on, the initial voltage V_O is independent of the capacitor C. Thus,

$$V_O = IR_D \qquad \text{Equation 4.22}$$

At any instant, the voltage from the power supply $V(t)$ is the sum of the voltage across R_D (V_D) and the voltage across C (V_C). Thus,

$$V(t) = V_D + V_C \qquad \text{Equation 4.23}$$

$$\frac{dV(t)}{dt} = \frac{dV_D}{dt} + \frac{dV_C(t)}{dt} \qquad \text{Equation 4.24}$$

During the electroosmotic dewatering process, the voltage across C (V_C) varies with time and V_D is a constant. Thus,

$$\frac{dV(t)}{dt} = \frac{dV_C(t)}{dt} \qquad \text{Equation 4.25}$$

Therefore, the change of voltage from the power supply per unit time is equal to the change of voltage across C (V_C) per unit time.

Substituting Equation 4.21 into Equation 4.18, the cumulative volume of collected water by electroosmosis is

$$Vol(t) = \frac{k_e AIR_D}{L} \int_0^t dt \qquad \text{Equation 4.26}$$

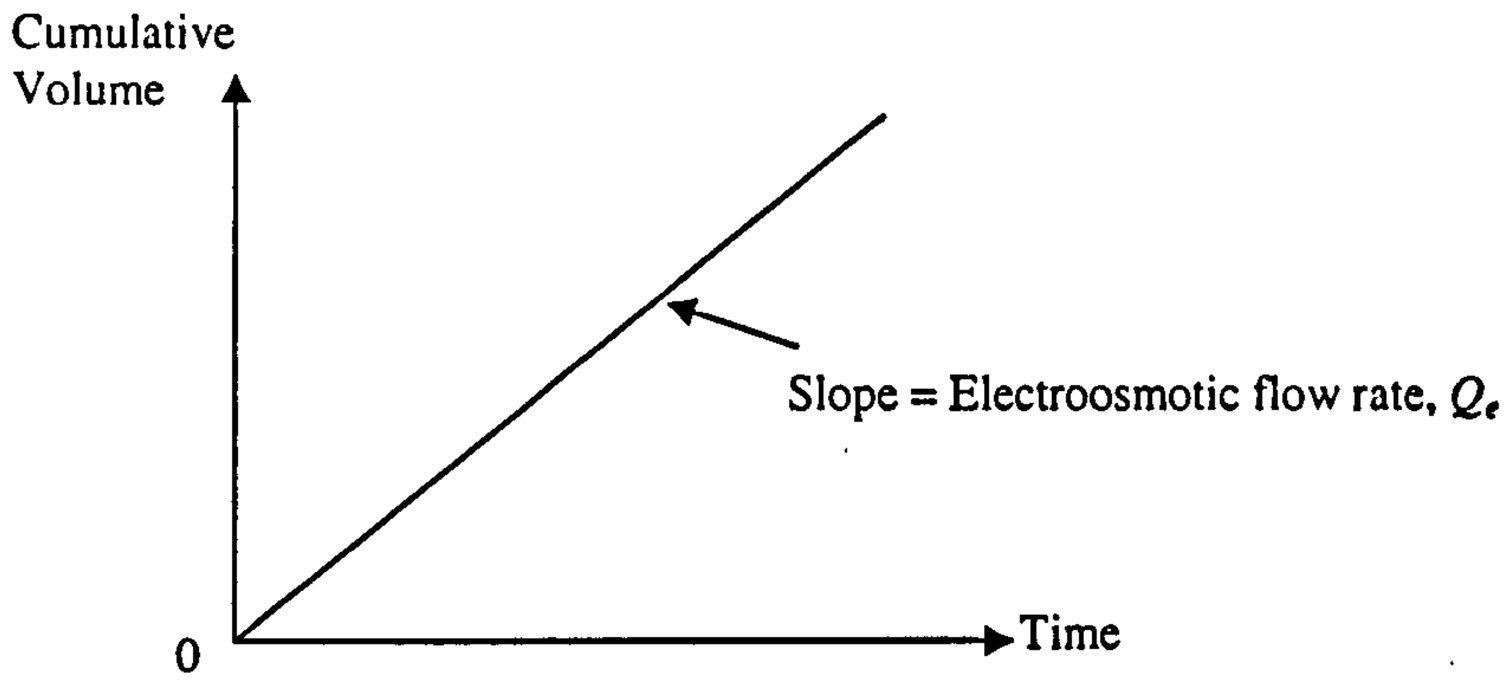


Figure 4.4 The relationship between cumulative volume and time when a sludge is dewatered with constant current

Substituting Equation 4.22 into Equation 4.26,

$$Vol(t) = \frac{k_e A I R_D t}{L} \qquad \text{Equation 4.27}$$

Equation 4.27 shows that the electroosmotic flow is linear with respect to time and proportional to the current when a sludge is electroosmotically dewatered with constant current. According to Equation 4.27, the relationship between the cumulative volume and time is represented by Figure 4.4.

4.3.4.1 ELECTROOSMOTIC FLOW RATE UNDER CONSTANT CURRENT

The slope of the graph of cumulative volume of collected water against time is the electroosmotic flow rate, Q_e in m^3/sec, which can be expressed as

$$Q_e = k_e i_e A R_O \qquad \text{Equation 4.28}$$

where k_e is the electroosmotic permeability (m^2/s-A-Ω), i_e is the current gradient $\Delta I/\Delta L$ (A/m) where I is the current (A) and L is the distance between two electrodes (m), A is the cross-sectional area (m^2) and R_O is the initial resistance (Ω).

According to Ohm's law, initial voltage is the product of current and initial resistance (i.e. $V_o = IR_o$). Therefore, the electroosmotic flow rate, Q_e, can be rewritten into the form of Helmholtz-Smoluchowski equation as

$$Q_e = k_e i_e A \qquad \text{Equation 4.29}$$

where k_e is the electroosmotic permeability (m^2/Vs) and i_e is the voltage gradient $\Delta V_O/\Delta L$ (V/m) where $V_o = IR_o$ and is the initial voltage (V).

Both Equations 4.28 and 4.29 can be used to calculate the electroosmotic flow rate for a dewatering system under constant current. The electroosmotic permeability, k_e, can be in units of either m^2/s-A-Ω or m^2/Vs. Both units are equivalent.

4.3.4.2 TESTING FOR DETERMINING ELECTROOSMOTIC PERMEABILITY

Electroosmotic permeability, k_e, can be determined by conducting a test using electroosmotic cell. Before the test starts, the cross-sectional area of the electroosmotic cell, A, and thickness of sludge, L, are measured. During the test, a constant current, I, is maintained so that I/L is the current gradient, i_e, and the cumulative volume of extracted water is measured with time. The reading of resistance at the start of the test is initial resistance, R_O. After the completion of the test, a linear graph of the cumulative volume of extracted water against time is plotted and the slope of the graph

represents the electroosmotic flow rate, Q_e. By substituting the values of Q_e, i_e, R_O and A into Equation 4.28, the electroosmotic permeability, k_e, can be calculated. Figure 4.5 illustrates the procedure of determining electroosmotic permeability.

4.4 EXPERIMENTAL PROGRAMME

In order to demonstrate the applicability of the design equations derived in Section 4.3, a series of experiments was conducted to investigate the relationship between the cumulative volumes of extracted water with time when sludge was dewatered under constant voltage and constant current conditions. The overall efficiency of electroosmotic dewatering of sludge based on the dewatering rate, final solid content and power consumption was also examined.

4.4.1 SLUDGE SAMPLE

According to the experimental results shown in Table 3.1, highest total volume extracted water and lowest energy consumption were obtained by electroosmotic dewatering of humic sludge. Humic sludge was therefore selected to be used in the experiment. The details of the sludge are described in Section 3.2.1.1.

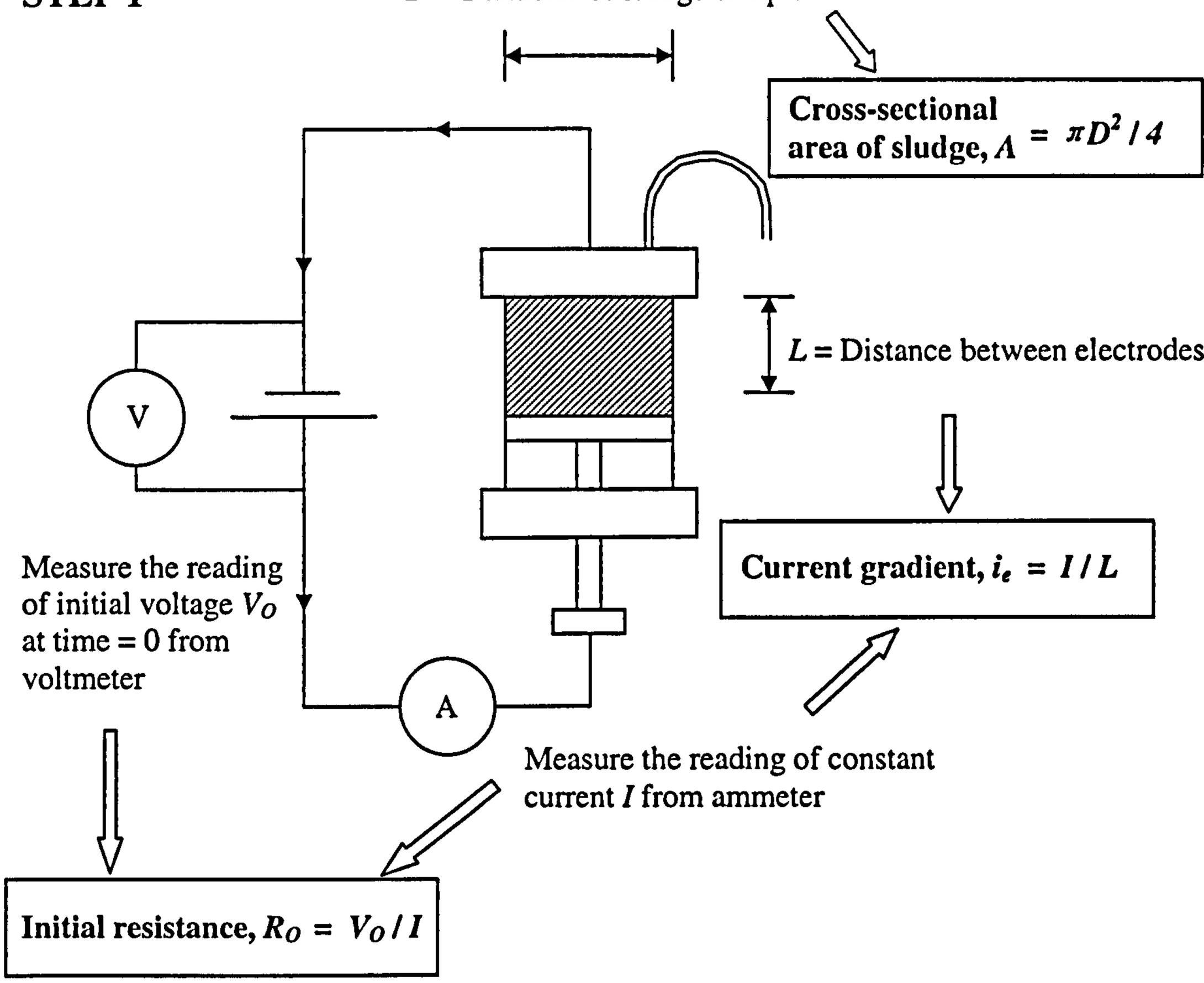
4.4.2 EXPERIMENTAL APPARATUS

A same experimental apparatus was used to that detailed in Sections 3.2.2 to 3.2.4.

4.4.3 EXPERIMENTAL SERIES 1 – ELECTROOSMOTIC DEWATERING WITH CONSTANT VOLTAGE

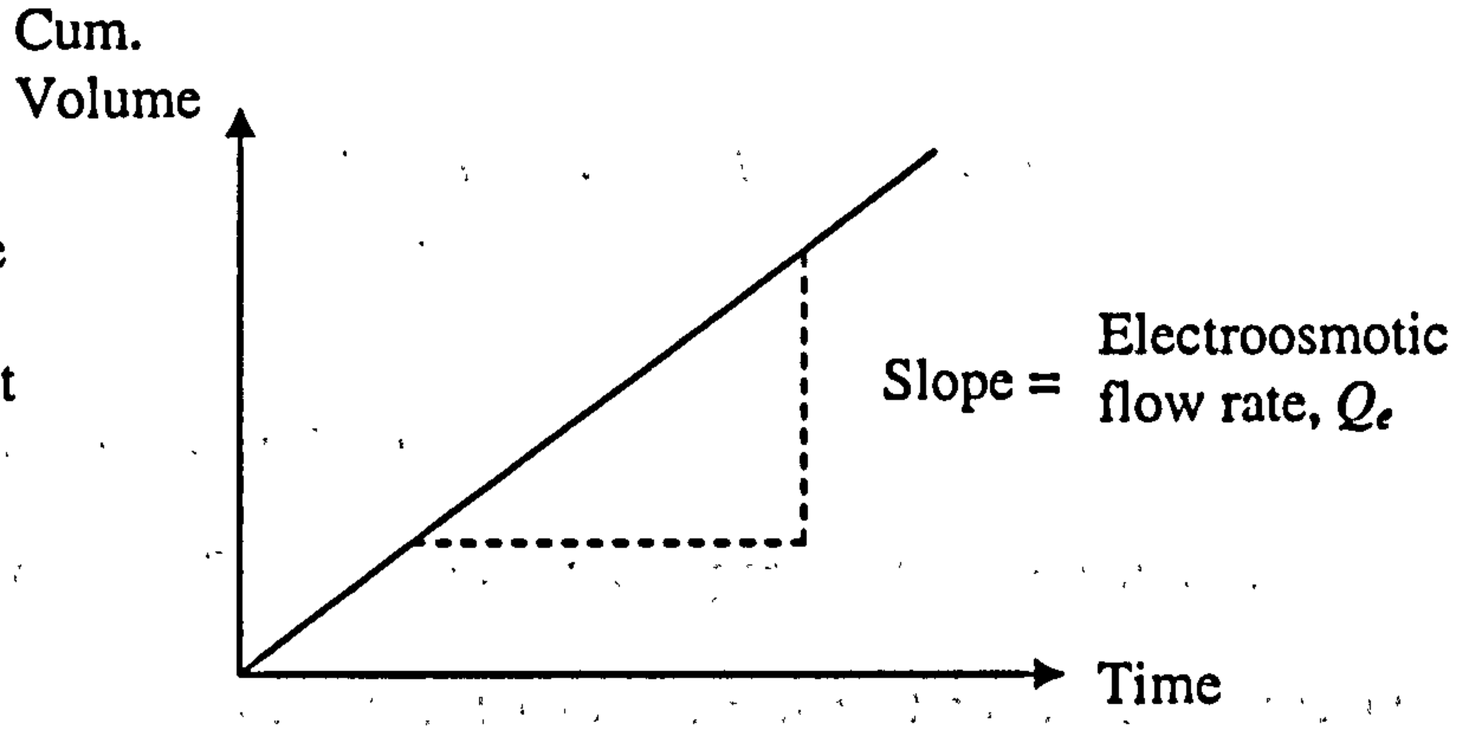
Initially, the electroosmotic cell was filled with 500g of sludge, equating approximately to a sample height of 30mm. A pressure of 25kPa was applied to the piston. At the same time, an external power supply provided a constant voltage of 10V across the disc

STEP 1



STEP 2

Measure the cumulative volume of extracted water with time and plot the graph of the cumulative volume of extracted against time



STEP 3

Substitute cross-sectional area of sludge, A, initial resistance, R_O, current gradient, i_e, and electroosmotic flow rate, Q_e, into Equation 4.28

$$Q_e = k_e i_e A R_O$$

Figure 4.5 Procedure of determining electroosmotic permeability

electrodes. Experiments were conducted for a total duration of 60 minutes, with readings taken of the current and cumulative volume of extracted water at 60 second intervals for the first 30 minutes, and subsequently, at 5 minute intervals. After the completion of each test, the solid content of the remaining sludge was measured. The experiments were repeated using an increased constant voltage of 15V.

4.4.4 EXPERIMENTAL SERIES 2 – ELECTROOSMOTIC DEWATERING WITH CONSTANT CURRENT

Using the same quantity of sludge as series one, a further series of experiments was conducted varying the applied pressure to 25kPa, 50kPa and 75kPa while keeping the current constant at 1A and 2A. The experiments were conducted over the same duration and intervals, but the readings were taken for the cumulative volume of extracted water and voltage until the voltage reached a maximum of 30V, when the readings of current were taken. After the completion of each test, the solid content of the remaining sludge was measured by weight.

4.4.5 EXPERIMENTAL SERIES 3 – ELECTROOSMOTIC DEWATERING WITH STEPPED CURRENT

The same quantity of sludge to that tested in series one and two was used. A pressure of 25kPa was applied to the piston. The duration of the experiment was 60 minutes.

During the experiment, the current was kept at 1A for the first 20 minutes, subsequently at 2A for the next 20 minutes, and at 1A for the last 20 minutes. The readings of the voltage and cumulative volume of extracted water were taken every minute. After the completion of the test, the solid content of the remaining sludge was measured by weight.

4.4.6 CONTROL

All the experiments were repeated using identical experimental conditions but without the application of electricity.

4.5 RESULTS AND DISCUSSION

4.5.1 EXPERIMENTAL SERIES 1 – ELECTROOSMOTIC DEWATERING WITH CONSTANT VOLTAGE

Figures 4.6 and 4.7 show the results from experimental series 1. Figure 4.6 illustrates that the cumulative volume of extracted water increased over time, but at an ever decreasing rate, as predicted by Equation 4.20. Figure 4.7 illustrates that current decreased exponentially with time, while the voltage remained constant, as predicted by Equation 4.15.

During the dewatering process with constant voltage, it is postulated that the electric field produced by the charges on the conducting plates creates an end-to-end alignment of molecular dipoles within the dielectric (sludge). The resulting positive and negative surface charges on the dielectric cause a reduction in the electric field within the dielectric. Furthermore, during the electrochemical reaction, resistance is increased, causing a reduction in electric field strength as well. Therefore, the resulting electric field strength in the dewatering system is less than the voltage gradient provided by the power supply ($\Delta V/\Delta L$). When dewatering with constant voltage, the flow rate decreases with time. The reason is that the resulting electric field strength decreases with time, as illustrated in Figure 4.8. Based on the analogy of charging a capacitor under a constant voltage, the variation of the current and the cumulative volume of extracted water would be expected to decay exponentially with time whereas the electroosmotic permeability

was assumed to be a constant. The experimental results have supported this hypothesis, as the graphs illustrate.

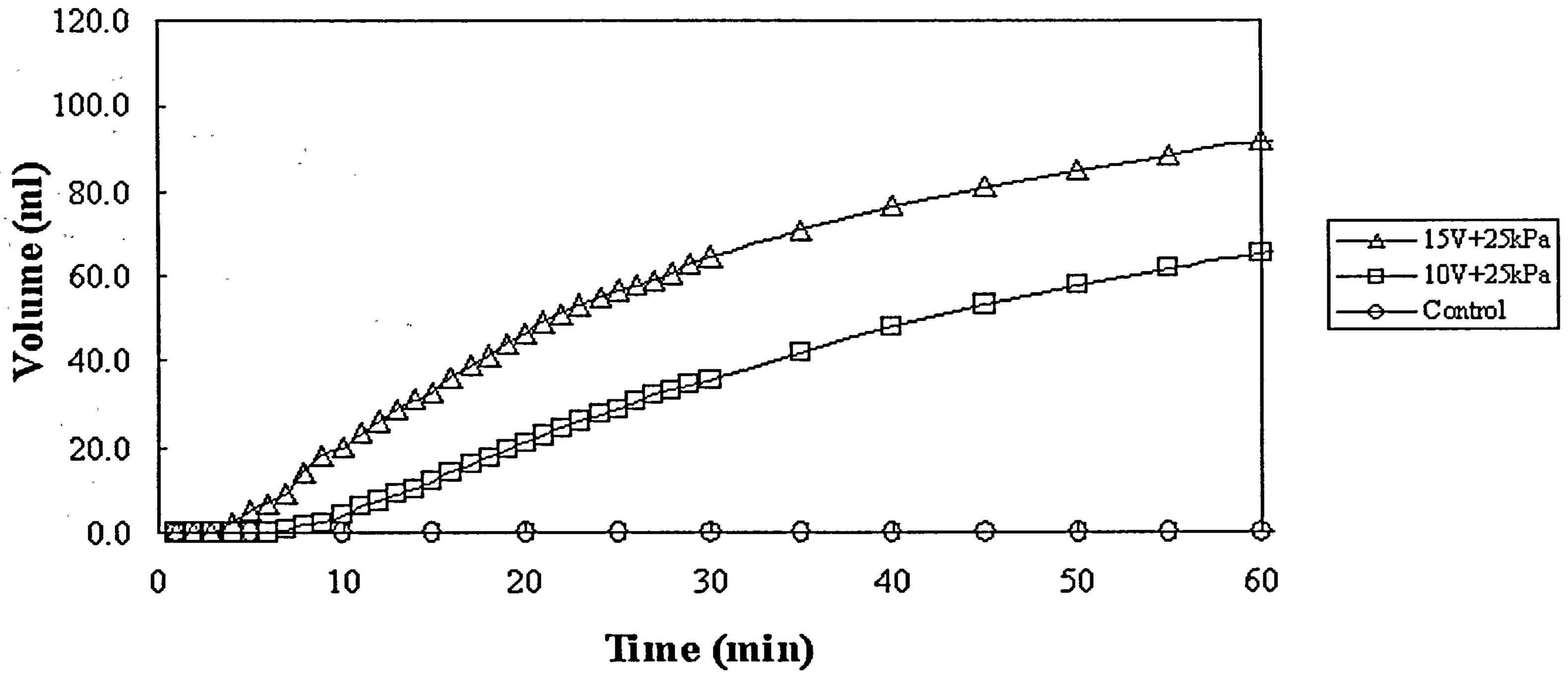


Figure 4.6 The results of experimental series 1 – Electroosmotic dewatering with constant voltage

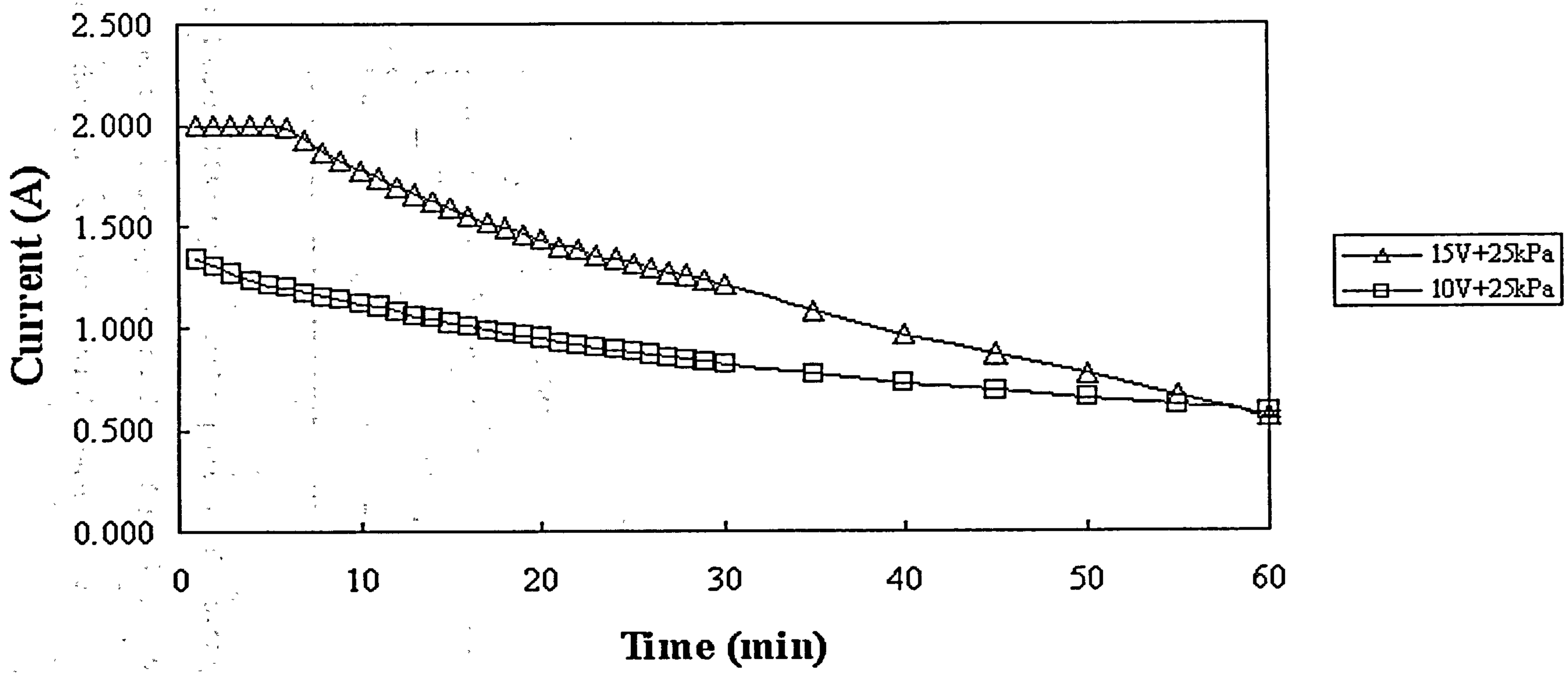


Figure 4.7 The results of experimental series 1 – Electroosmotic dewatering with constant voltage

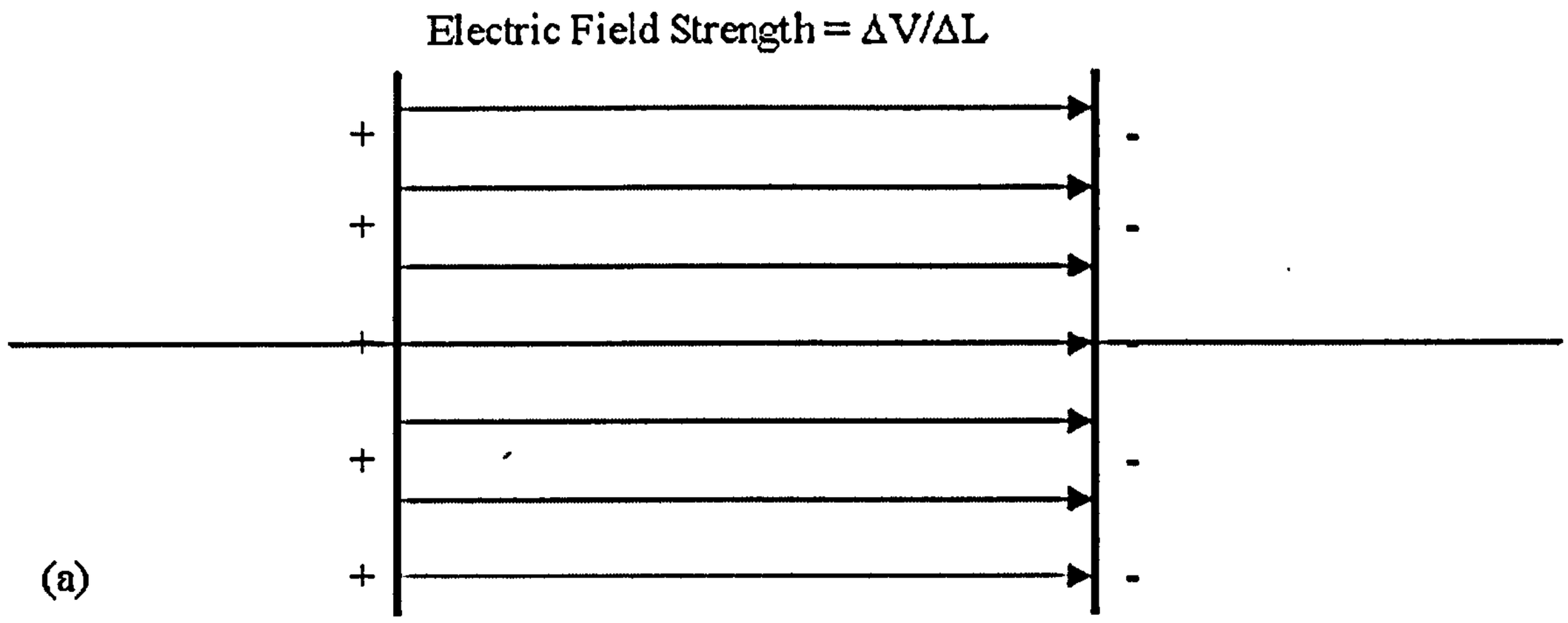


Figure 4.8 (a) Electric field strength produced by power supply. (b) Opposing E-field due to surface charge of the dielectric. (c) Resistance due to electrochemical reaction causes a reduction in E-field

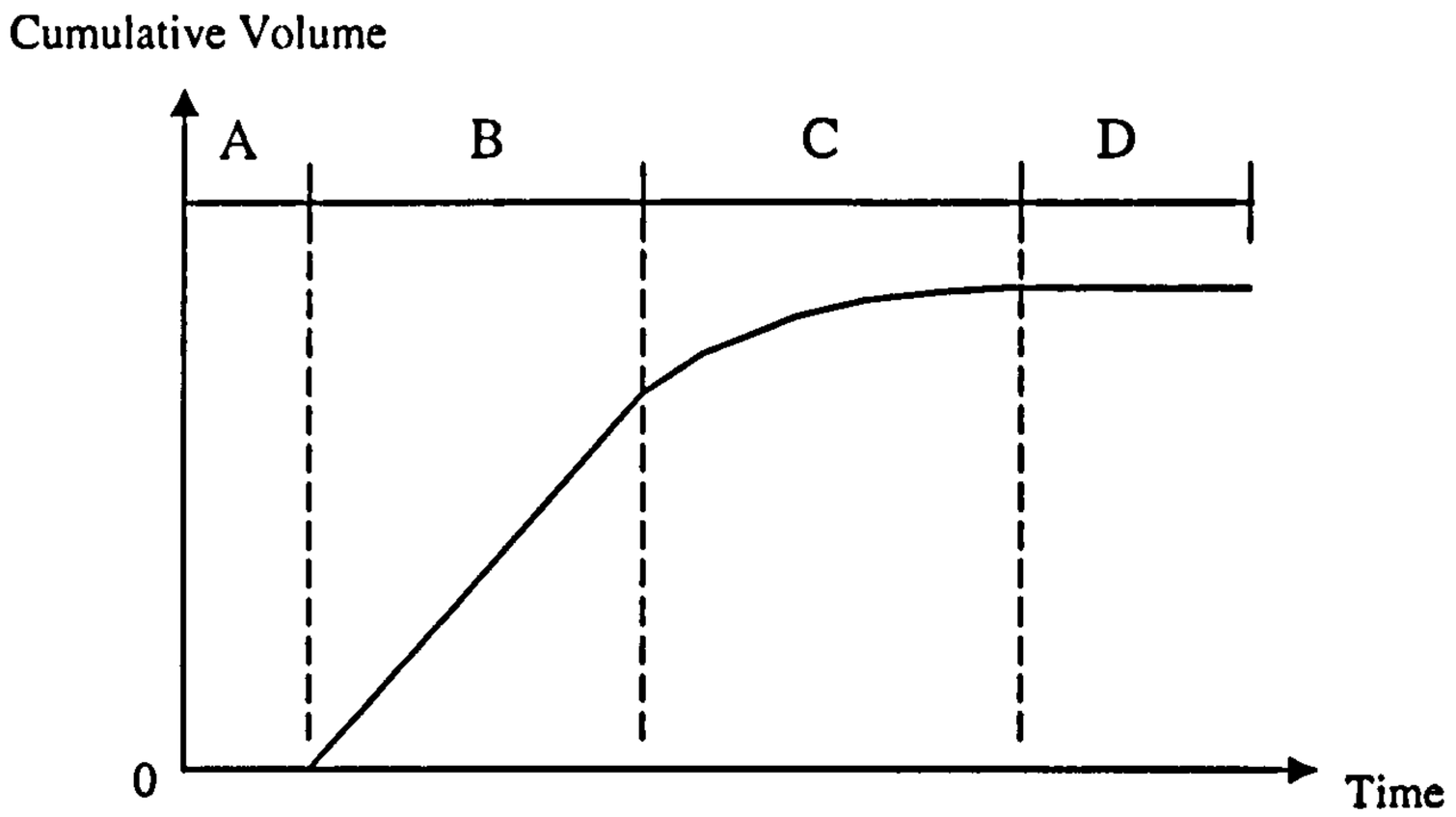


Figure 4.9 Four stages of the experimental results with electroosmotic dewatering with constant current

4.5.2 EXPERIMENTAL SERIES 2 – ELECTROOSMOTIC DEWATERING WITH CONSTANT CURRENT

These experiments were conducted maintaining a constant current, the results of which are shown in Figures 4.10 and 4.11. They show graphs of the relationship between cumulative volume of extracted water and time. It can be seen that the experimental results can be separated into 4 distinct stages. With reference to Figure 4.9, stage A is a period when no water is extracted from the sample and may be regarded as the time needed for the extracted water to fill up the void at the top of the cell, and the tube to the collecting vessel.

During stage B, the cumulative volume of extracted water has a linear relationship with time as constant current is maintained. This relationship remains until the voltage reaches the maximum voltage output of the power supply, which, in this experiment, was 30V. Equation 4.27 shows this relationship clearly.

During stage C, the power supply cannot maintain constant current, as the resistance of the sludge is too high. As a result, the rate of the water extraction decreases as the current is dropped. Under these conditions, the dewatering process is similar to electroosmotic dewatering under constant voltage when the cumulative volume of extracted water against time is governed by Equation 4.20. Throughout stage C, the current is decreasing with time until the resistance is too high, at which point the electroosmotic dewatering process has effectively stopped. By stage D, the cumulative volume of extracted water is constant, and no further water is being extracted.

4.5.3 EXPERIMENTAL SERIES 3 – ELECTROOSMOTIC DEWATERING WITH STEPPED CURRENT

The results of experimental series 3 are shown in Figure 4.12. It can be seen that a linear relationship between cumulative volume of extracted water and time was obtained when sludge was dewatered under constant current. The results also show that the electroosmotic flow increased with increase in current. For the first 20 minutes, the current was kept at 1A. No water was collected from the sample for the first 6 minutes. This period was regarded as the time needed for the extracted water to fill up the void at the top of the cell and the tube to the collecting vessel, as discussed in Section 4.5.2. For the time from 6 to 20 minutes, 28ml of extracted water was collected. Subsequently, 81ml of extracted water was collected in the next 20 minutes when 2A of current was maintained. For the last 20 minutes, the current was kept at 1A again and 40ml of extracted water was collected.

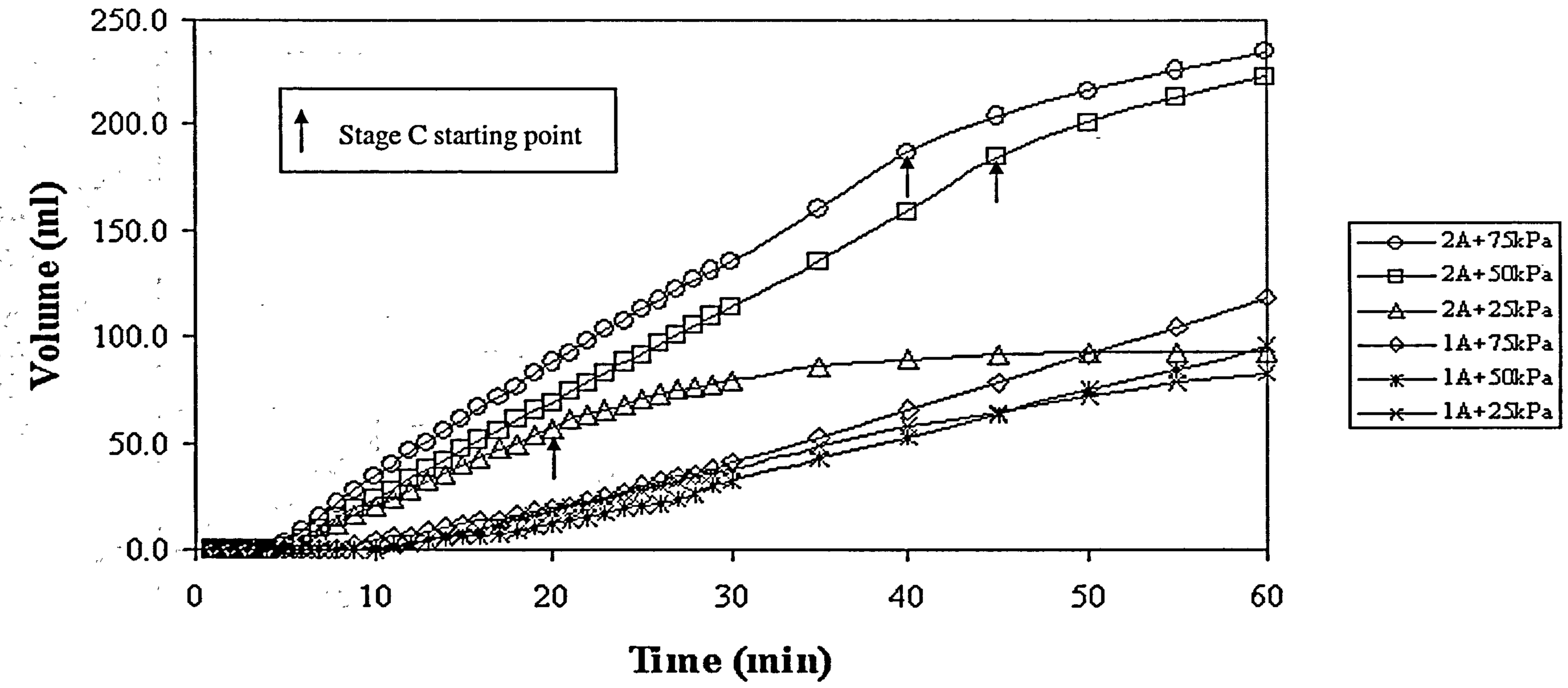


Figure 4.10 The results of experimental series 2 – Electroosmotic dewatering with constant current

Linear Relationship of Cumulative Volume of Extracted Water against Time in Stage B

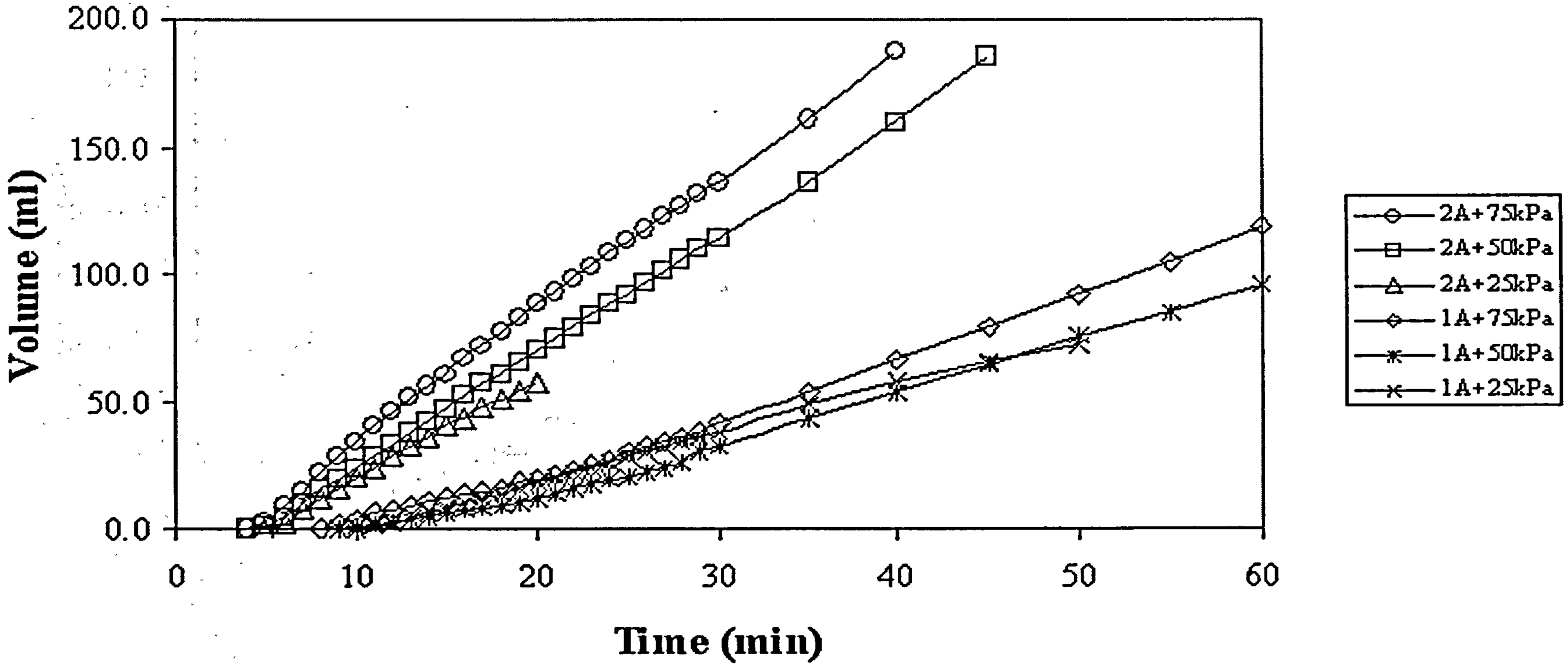


Figure 4.11 The results of experimental series 2 – Electroosmotic dewatering with constant current

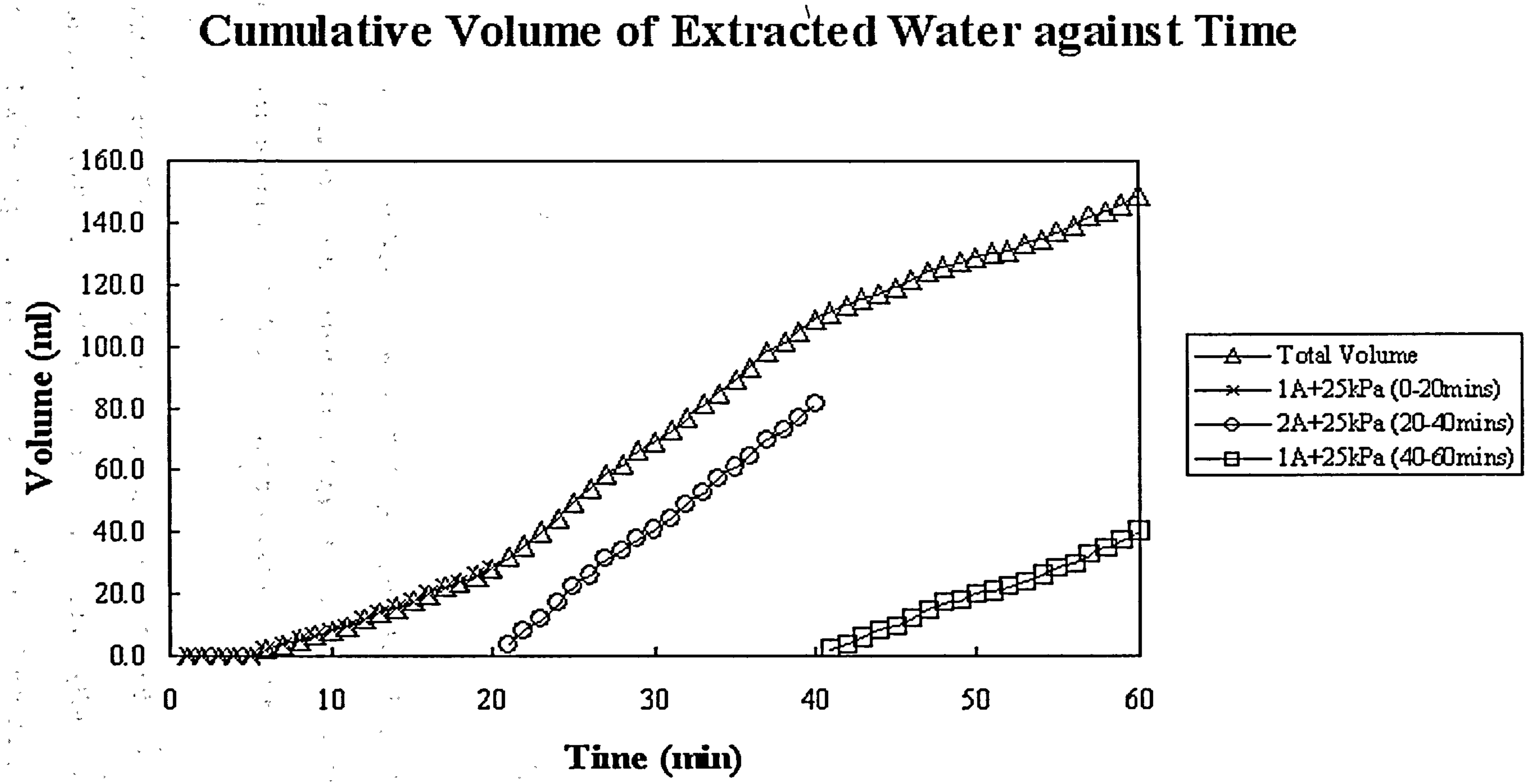


Figure 4.12 The results of experimental series 3 – Electroosmotic dewatering with stepped current

Using the Equation 4.28, the values of electroosmotic permeability, k_e, for different periods were calculated. They were 5.74 x $10^{-9}m^2/Vs$ for the first 20 minutes, 5.81 x $10^{-9}m^2/Vs$ for the next 20 minutes and 5.74 x $10^{-9}m^2/Vs$ for the last 20 minutes. The results show that the electroosmotic permeability, k_e, was nearly a constant during the dewatering process. Moreover, the value of electroosmotic permeability was not affected by the change of current intensity. These findings imply that the value of electroosmotic permeability can be assumed to be a constant for the design of an electroosmotic dewatering process under constant current using the design equations derived in Section 4.3.

4.5.4 EXTERNAL AND INTERNAL VOLTAGE GRADIENTS

In the electroosmotic dewatering system, the external voltage gradient should be defined as the voltage gradient provided by the power supply, whereas the internal voltage gradient is the resulting electric field strength which is used to generate the electroosmotic flow. Mathematically, the internal voltage gradient is defined as

$$\frac{\Delta V_{internal}}{\Delta L} = \frac{\Delta V_{external} - V_C - IR_V}{\Delta L} \qquad \text{Equation 4.30}$$

where $\Delta V_{external}$ is the voltage provided by the power supply, V_C is the potential difference across the capacitor, I is the current, R_V is the variable resistance due to electrochemical reactions, and ΔL is the distance between electrodes.

It is indicated from Equation 4.25 that the change of voltage from the power supply per unit time is equal to the change of voltage across the capacitor C (V_C) per unit time during the dewatering process with constant current. Considering that electrochemical

reactions exist during the electroosmotic dewatering, the change of voltage from the power supply can be rewritten as

$$\frac{dV_{external}(t)}{dt} = \frac{dV_C(t)}{dt} + \frac{dIR_V(t)}{dt} \qquad \text{Equation 4.31}$$

Equation 4.31 shows that the loss of electric field strength due to the surface charge of the dielectric (Figure 4.8b) and electrochemical reactions (Figure 4.8c) can be compensated by the power supply. Therefore, no matter how much the electrochemical reactions change the resistance of the dewatering system, the resulting electric field strength (internal voltage gradient) is always kept constant when dewatering with constant current. In other words, dewatering with constant current is the way to maintain a constant internal voltage gradient to generate a constant electroosmotic flow by increasing the external voltage gradient.

The advantages of dewatering by maintaining constant current over constant voltage are (1) a constant electroosmotic flow rate is provided; (2) the voltage drawn by resistance due to the effect of electrochemical reactions is compensated by power supply so that electrochemical reactions can be ignored in the design; and (3) using a linear relationship between flow and time simplifies the design process. As a result, in order to simplify the design process, electroosmotic dewatering of sludge should be achieved by maintaining constant current, instead of constant voltage.

4.5.5 EFFICIENCY OF ELECTROOSMOTIC DEWATERING

The efficiency of electroosmotic dewatering was assessed, based on the dewatering rate, final solid content and power consumption achieved by each experiment. The cumulative volume of extracted water and final solids after 60 minutes are summarized

in Table 4.2 for each experiment. The results show that increasing the voltage improved the efficiency of the dewatering process. At a pressure of 25kPa, with a constant voltage of 15V, a total of 92ml of water was extracted as compared to 65ml of water at 10V and no water extracted at 0V. The final solid content obtained at 15V was 20.2%, as compared to 16.1% with no voltage.

At constant current and pressure, a higher current resulted in more water being extracted. Applying 75kPa and maintaining 2A produced the greatest quantity of extracted water (235ml), resulting in a final solid content of 29.2%.

The energy consumption for electroosmotic dewatering varied with the applied pressure, voltage and current ranging between 0.085 and 0.323kWh/kg of extracted water. 1kg of water requires approximately 1.2kWh to be evaporated using heat alone. Compared to thermal drying, energy consumption for electroosmotic dewatering is less. At the same pressure, a higher applied voltage and current resulted in higher energy consumption. This was because high applied voltage and current increase the rate of electrochemical reaction, which increases the electrical resistance, thus leading to energy loss.

4.6 CHAPTER SUMMARY

The Helmholtz-Smoluchowski theory is the earliest and most widely used to calculate the electroosmotic flow. However, electroosmotic flow rate decreases with time due to electrochemical reactions so that the use of the Helmholtz-Smoluchowski flow equation together with the assumptions of no electrochemical reaction and a constant electroosmotic permeability cannot predict the dewatering process under constant voltage accurately.

This chapter sets out the framework for such a design methodology, founded on the mathematics of simple electrical circuits and demonstrated by laboratory experimentation. It concludes that the electroosmotic flow rate decreases with time when a sludge is electroosmotically dewatered with constant voltage whereas the electroosmotic flow rate is constant with respect to time when a sludge is dewatered with constant current.

Both electroosmotic dewatering under constant voltage and constant current were found to be effective and potentially economic to dewater sludge, in accordance with the finding shown in Chapter 3. The advantages of dewatering by maintaining constant current over constant voltage are: (1) a constant electroosmotic flow rate is provided; (2) the voltage drawn by resistance due to the effect of electrochemical reactions is compensated by power supply so that electrochemical reactions can be ignored in the design; and (3) using a linear relationship between flow and time simplifies the design process. Thus it is recommended that electroosmotic dewatering of sludge should be achieved by maintaining constant current, instead of constant voltage.

Table 4.2 Experimental results: Cumulative volume of extracted water, final solids and energy consumption after 60 minutes

Electroosmotic Dewatering with Constant Voltage					
Pressure (kPa)	Constant Voltage (V)	Volume of Extracted Water (ml)	Initial Solids (%)	Final Solids (%)	Energy Consumption (kWh/kg of extracted water)
25	15	92	16.4	20.2	0.203
25	10	65	15.3	17.6	0.133
Electroosmotic Dewatering with Constant Current					
Pressure (kPa)	Constant Current (A)	Volume of Extracted Water (ml)	Initial Solids (%)	Final Solids (%)	Energy Consumption (kWh/kg of extracted water)
25	2	93	16.4	20.1	0.323
25	1	83	16.5	19.8	0.185
50	2	223	15.4	27.8	0.169
50	1	96	16.2	20.0	0.099
75	2	235	15.5	29.2	0.158
75	1	118	16.1	21.1	0.085
Electroosmotic Dewatering without Electricity (Control)					
Pressure (kPa)	Constant Current (A)	Volume of Extracted Water (ml)	Initial Solids (%)	Final Solids (%)	Energy Consumption (kWh/kg of extracted water)
25	0	0	16.1	16.1	-
50	0	13	16.2	16.6	-
75	0	16	16.1	16.6	-

* For comparison, 1kg of water needs approximately 1.2kWh to be evaporated

CHAPTER 5

DESIGN PARAMETERS FOR ELECTROOSMOTIC DEWATERING OF SLUDGE USING CONSTANT CURRENT

5.1 INTRODUCTION

Electroosmotic dewatering with constant voltage and constant current were found to be effective and economic to dewater sludge in Chapter 3 and Chapter 4 respectively. The design equations for both approaches have been derived in Chapter 4, founded on the mathematics of simple electrical circuits and demonstrated by laboratory experimentation. It concludes that electroosmotic dewatering of sludge with constant current not only enhanced the sludge dewatering efficiency, but also had the advantage of simplifying design procedures over those required for electroosmotic dewatering of sludge using constant voltage. This is because the electroosmotic dewatering with constant current can produce a constant electroosmotic flow rate (linear relationship between flow and time) whereas electroosmotic dewatering with constant voltage produces an electroosmotic flow rate that varies with time of treatment. For the purpose of simplifying the design process, it is suggested that electroosmotic dewatering of sludge should be achieved by maintaining constant current, instead of constant voltage.

Previously, electroosmotic dewatering is achieved by maintaining constant voltage. Electroosmotic dewatering of sludge under constant current is a new technique and the design concept of dewatering under constant current are different from constant voltage. This chapter derives design equations to calculate the final solid concentration of sludge and treatment time, explores in further detail each of the

parameters that constitute the design framework, investigates the effects of the design parameters on the dewatering process and presents a more detailed design methodology.

5.2 DERIVING TREATMENT TIME IN TERMS OF INITIAL AND FINAL SOLID CONCENTRATIONS

Dewatering of sludge is the process that increases the solids content of sludge, thereby, for example, reducing the volume of water being transported with the sludge, or reducing the volume of water to be driven off during incineration, depending on the final disposal option. In the design of an electroosmotic dewatering system, it should be possible to estimate the treatment time required to increase the solid content of the sludge from a low initial solid concentration to high final solid concentration. Moreover, there is need for engineers to design an efficient dewatering system which can achieve a particular final solid concentration of sludge within a particular treatment time. Therefore, treatment time is one of the most important factors to be considered in the dewatering system and it is necessary to derive the treatment time of the electroosmotic dewatering system in terms of initial and final solid concentrations. In the electroosmotic cell as described in Section 3.2.2, the volume of the sludge in the cell, V, is the product of the cross-sectional area of the cell and the thickness of the sludge:

$$V = AL \qquad \text{Equation 5.1}$$

where A is the cross-sectional area of the sludge and L is the thickness of the sludge.

The density of the sludge is expressed as:

$$\rho_s = \frac{M}{V} \qquad \text{Equation 5.2}$$

where ρ_s is the density of the sludge, M is the total mass of the sludge in the cell and V is the volume of the sludge in the cell.

Substituting Equation 5.1 into Equation 5.2, the total mass of the sludge is

$$M = \rho_s AL \qquad \text{Equation 5.3}$$

Before the treatment, the solid concentration of sludge is

$$SD_1 = \frac{m_s}{M} \qquad \text{Equation 5.4}$$

where SD_1 is the initial solid concentration of the sludge and m_s is the mass of dry solid.

After the electroosmotic dewatering process, the solid concentration is

$$SD_2 = \frac{m_s}{M - Vol} \qquad \text{Equation 5.5}$$

where SD_2 is the final solid concentration of the sludge and Vol is the volume of water collected to reach the solid concentration from SD_1 to SD_2.

Substituting Equation 5.4 into Equation 5.5, therefore

$$SD_2 = \frac{M \times SD_1}{M - Vol} \qquad \text{Equation 5.6}$$

Rearranging,

$$Vol = \frac{(SD_2 - SD_1)M}{SD_2} \qquad \text{Equation 5.7}$$

By substituting Equation 4.27 into Equation 5.7, the required treatment time to obtain the desired solid concentration from SD_1 to SD_2 is

$$t = \left(\frac{SD_2 - SD_1}{SD_2}\right)\frac{\rho_s L^2}{k_e I R_o} \qquad \text{Equation 5.8}$$

By rewriting the Equation 5.8, the final solid concentration after a particular treatment time is

$$SD_2 = \frac{SD_1}{1 - \frac{k_e I R_o t}{\rho_s L^2}} \qquad \text{Equation 5.9}$$

From Equation 5.8 and Equation 5.9, it can be seen that increasing the treatment time increases final solid concentration, as expected. As discussed in Section 2.3, electroosmotic dewatering can be applied to remove free, vicinal and capillary water, but not the chemically bound water. Therefore, the upper limit of SD_2 ($SD_{2,\,upper}$) is

$$SD_{2,\,upper} = \frac{m_s}{m_s + m_c} \qquad \text{Equation 5.10}$$

where m_c is the mass of chemically bound water.

5.3 DESIGN PARAMETERS FOR DEWATERING UNDER CONSTANT CURRENT

From Equations 5.8 and 5.9, the required treatment time and the final solid concentration are a function of sample thickness and current. Due to increase in resistance with time and the limit of maximum voltage output from the power supply, both Equation 5.8 and Equation 5.9 are not applicable when the current cannot be kept constant. Therefore, the time over which constant current could be maintained is an important design parameter that should be considered very carefully in the design process. When an electroosmotic sludge treatment system is used in practice, it will be used in conjunction with a conventional system, such as belt press or filter press. The dewatering process will be a function of an additional set of parameters including power supply, applied pressure and type of electrodes. The theoretical basis and design requirements for each of these design parameters will be discussed herein.

5.3.1 SAMPLE THICKNESS

From Equation 5.8, it is clearly seen that the treatment time is directly proportional to the square of the sample thickness:

$$t \propto L^2 \qquad \text{Equation 5.11}$$

Therefore, the time required to obtain the desired final solid concentration is longer when the thickness of the sludge is increased. Conversely, the required time would be shortened by decreasing the thickness. For example, an electroosmotic cell requires time T_1 to reduce the water content of sample sludge with thickness of L by applying a constant current I from x%d.s. to $2x$%d.s.. However, if the thickness of sludge is half of original thickness, the required time to obtain desired solid concentration from x%d.s. to $2x$%d.s., T_2, will be decreased to half of its original treatment time (i.e. T_2 =

$T_1 / 2$). The calculations are shown as below:

The required time if thickness = L is

$$T_1 = \left(\frac{2x - x}{2x}\right)\left(\frac{\rho_s L^2}{k_e I R_O}\right)$$

$$T_1 = \frac{\rho_s L^2}{2k_e I R_O} \qquad \text{Equation 5.12}$$

When the thickness of sludge becomes half of its original thickness, the initial resistance also becomes half of its value as resistance is proportional to thickness according to the standard resistance equation, i.e.

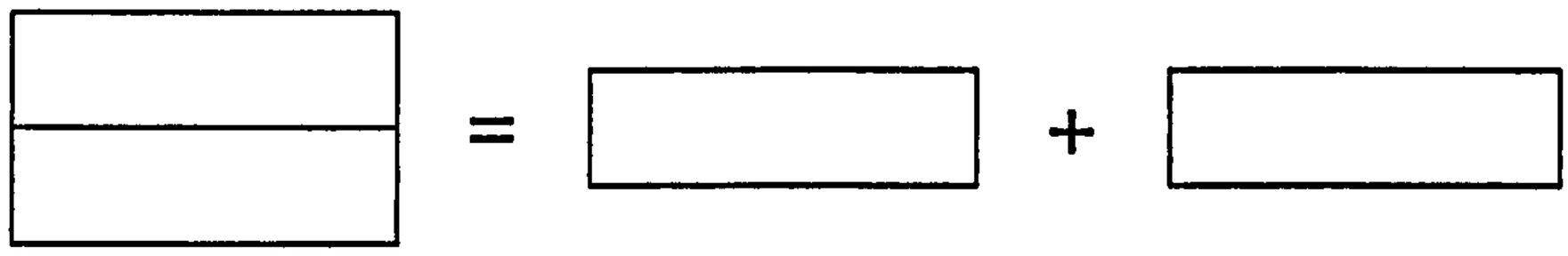
$$R = \rho \frac{L}{A} \qquad \text{Equation 5.13}$$

where ρ is the resistivity, L is the conductor length and A is the conductor cross-sectional area.

Therefore, the required time if thickness = $L / 2$ is

$$T_2 = \left(\frac{2x - x}{2x}\right)\left(\frac{\rho_s (L/2)^2}{k_e I (R_O/2)}\right) \qquad \text{Equation 5.14}$$

$$T_2 = \frac{\rho_s L^2}{4k_e I R_O} \qquad \text{Equation 5.15}$$



Total Treatment = T_1 Total Treatment = $T_1 / 2 + T_1 / 2 = T_1$

Figure 5.1 Total treatment time of dewatering sludge with thickness of L and $L / 2$

Substituting Equation 5.14 into Equation 5.15,

$$T_2 = T_1 / 2 \qquad \text{Equation 5.16}$$

It seems that decreasing the thickness of sludge saves the treatment time. However, it is not true. This is because, for treating the same amount of sludge, the dewatering treatment with half of original sludge thickness has to be run twice so that the total treatment time will be the same as the treatment time with the original sludge thickness. This is illustrated in Figure 5.1. Therefore, the thickness of sludge does affect the treatment time when applying the concept of dewatering with constant current.

On the other hand, from Equation 4.28, it is seen that the electroosmotic flow rate, Q_e, is dependent on the cross-sectional area, A, and the current gradient i_e, which is equal to $\Delta I/\Delta L$, where I is current and L is sample thickness. It would appear that the electroosmotic flow rate, Q_e, is also a function of cross-sectional area, A, and sample thickness, L. However, this is not the case when applying the concept of dewatering with constant current because both cross-sectional area, A, and sample thickness, L, are eliminated after substituting Equation 5.13 into Equation 4.28:

$$Q_e = \frac{k_e I A}{L} \times \frac{\rho L}{A} \qquad \text{Equation 5.17}$$

Rearranging,

$$Q_e = k_e I \rho \qquad \text{Equation 5.18}$$

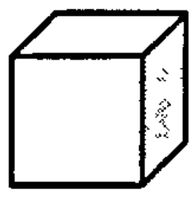
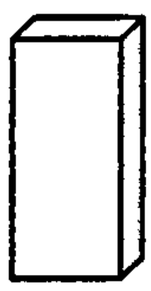
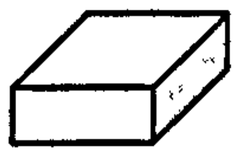
Therefore, the electroosmotic flow rate under constant current is a function of electroosmotic permeability, k_e, applied current, I, and initial resistivity, ρ. It is independent of the dimension of the sludge (cross-sectional area, A, and sample thickness, L). The dimensions of the sludge affect its initial resistance only. Table 5.1 illustrates how the change of the dimensions of sludge affects the electroosmotic flow rate under two dewatering approaches (constant voltage and constant current). Sludge with the same volume of $1m^3$, resistivity of $1\Omega m$ and electroosmotic permeability of $5 \times 10^{-9} m^2/Vs$ but different dimensions is electroosmotically dewatered with constant voltage of 1V and constant voltage of 1A. It can be seen that the electroosmotic flow rate under constant voltage varies with the dimensions of the sludge (cross-sectional area, A, and sample thickness, L), whereas the electroosmotic flow rate under constant current does not. This is the main difference between the two dewatering approaches. Therefore, when designing an electroosmotic dewatering system under constant current, there is no need to consider the effect of the dimensions of the sludge on the electroosmotic flow rate.

5.3.2 APPLIED CURRENT

From Equation 5.8, it can be seen that treatment time is inversely proportional to the current:

$$t \propto \frac{1}{I} \qquad \text{Equation 5.19}$$

Table 5.1 The effect of change of dimension of sludge on the electroosmotic flow rate

Dimensions	Resistance of sludge $(R_O = \rho\frac{L}{A})$	Electroosmotic flow rate under constant voltage of 1V $(Q_e = k_e i_e A)$	Electroosmotic flow rate under constant current of 1A $Q_e = k_e i_e A R_O$
 L = 1m A = 1m²	$R_O = 1\times\frac{1}{1}\Omega$ $R_O = 1\Omega$	$Q_e = 5\times10^{-9}\times\frac{1}{1}\times1m^3/s$ $Q_e = 5\times10^{-9}\ m^3/s$	$Q_e = 5\times10^{-9}\times\frac{1}{1}\times1\times1m^3/s$ $Q_e = 5\times10^{-9}\ m^3/s$
 L = 2m A = 0.5m²	$R_O = 1\times\frac{2}{0.5}\Omega$ $R_O = 4\Omega$	$Q_e = 5\times10^{-9}\times\frac{1}{2}\times0.5m^3/s$ $Q_e = 1.25\times10^{-9}\ m^3/s$	$Q_e = 5\times10^{-9}\times\frac{1}{2}\times0.5\times4m^3/s$ $Q_e = 5\times10^{-9}\ m^3/s$
 L = 0.5m A = 2m²	$R_O = 1\times\frac{0.5}{2}\Omega$ $R_O = 0.25\Omega$	$Q_e = 5\times10^{-9}\times\frac{1}{0.5}\times2m^3/s$ $Q_e = 2\times10^{-8}\ m^3/s$	$Q_e = 5\times10^{-9}\times\frac{1}{0.5}\times2\times0.25m^3/s$ $Q_e = 5\times10^{-9}\ m^3/s$

Therefore, the time required to obtain a desired final solids concentration would be shorter when the applied current is increased. Moreover, Equation 4.27 shows that the cumulative volume of extracted water is linear with respect to time and proportional to the applied current and Equation 5.18 shows that the electroosmotic flow rate is directly proportional to current. Current may be defined as the rate of movement of charge. In the case of electroosmosis, the movement of charge is, effectively, the movement of the cations bound to the solid particle surface under the influence of the electric field. The movement of this layer of cations drags the bulk

pore water with it so that the flow velocity depends on the rate of movement of charge (current). Therefore, higher current results in more water being extracted and higher electroosmotic flow rate.

In the design of an electroosmoic dewatering system, it is necessary to choose an appropriate current to dewater sludge for achieving a particular final solid concentration within a particular treatment time. By rewriting Equation 5.8, the current required to obtain the desired solid concentration within a particular treatment time is

$$I = \left(\frac{SD_2 - SD_1}{SD_2}\right)\frac{\rho_s L^2}{k_e t R_o} \qquad \text{Equation 5.20}$$

From Equation 5.8, it can be seen that final solid concentration is increased by increasing the current in a particular treatment time.

5.3.3 TIME OVER WHICH CONSTANT CURRENT COULD BE MAINTAINED

In Chapter 4, it is stated that the experimental results with electroosmotic dewatering with constant current can be separated into 4 district stages. During stages A and B, the cumulative volume of extracted water has a linear relationship with time as constant current is maintained. Stage C starts when the power supply cannot maintain constant current as the resistance of the sludge is too high. As a result, the current drops and the rate of the water extraction decreases until stage D at which the electroosmotic dewatering process has effectively stopped and no further water is being extracted. The time from the start of dewatering treatment to the end of stage B, which is defined as the length of time over which constant current could be

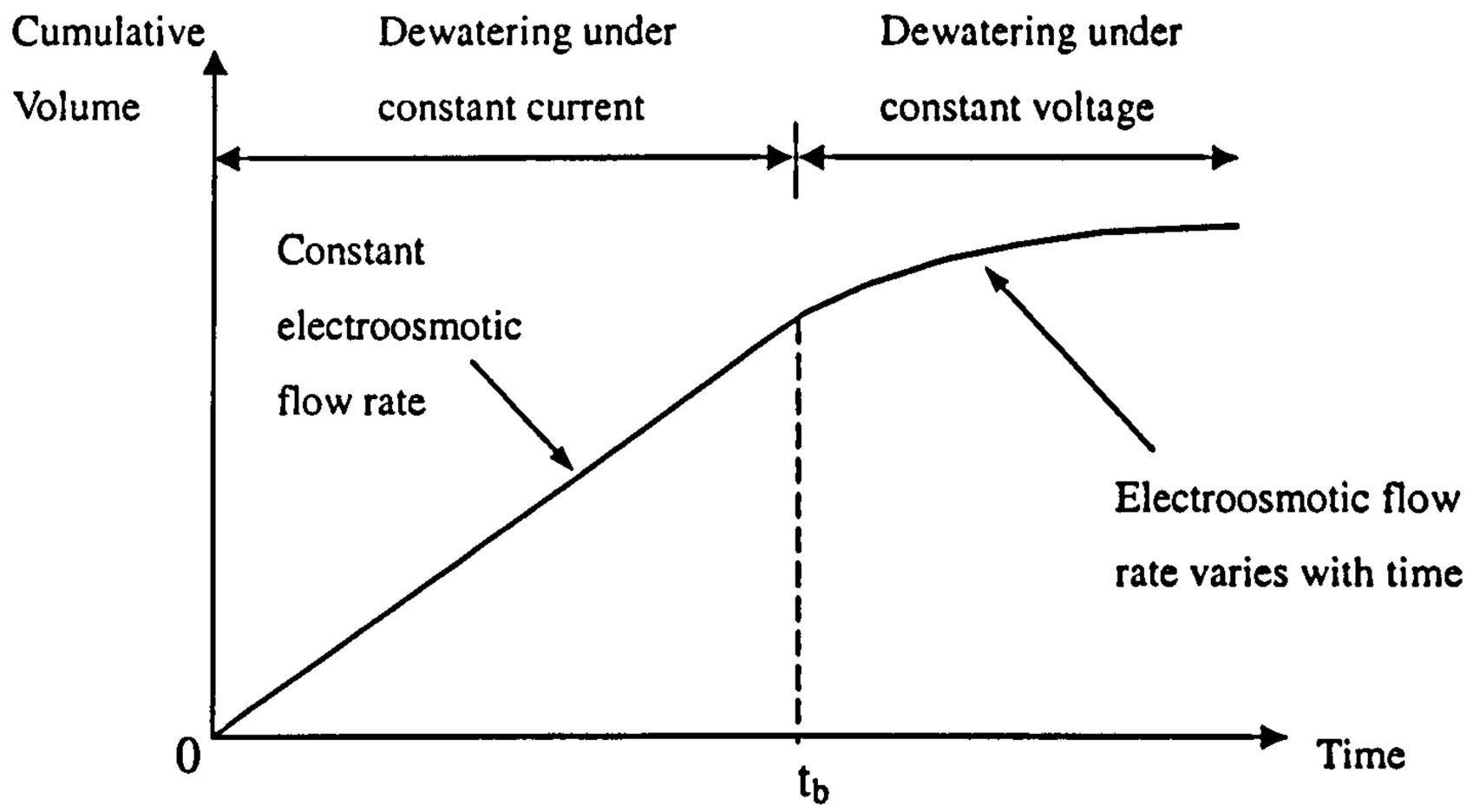


Figure 5.2 Typical experimental results of dewatering under constant current

maintained, t_b, is illustrated in Figure 5.2.

During the period of constant current, t_b, the linear relationship between electroosmotic flow and time holds true. Therefore, the design equations derived in Section 5.2 (Equations 5.8 and 5.9) are only valid within this period. In order to estimate the required treatment time to obtain the desired solid concentration of sludge by using Equation 5.8, it is necessary to ensure that the estimated treatment time is less than the time over which constant current could be maintained, t_b, otherwise the estimated treatment time is not accurate and less than the actual required treatment time to obtain the desired solid concentration. Similarly for calculating the final solid concentration of sludge after a particular treatment time by using Equation 5.9, it is necessary to ensure that the particular treatment time is less than t_b, otherwise, the estimated final solid concentration is not accurate and less than the actual value.

5.3.4 POWER SUPPLY

The resistance of the electroosmotic dewatering system is a minimum when the dewatering treatment starts (i.e. $R_O = V_O / I$). During the dewatering process, the voltage from the power supply needs to be increased with time of treatment in order to

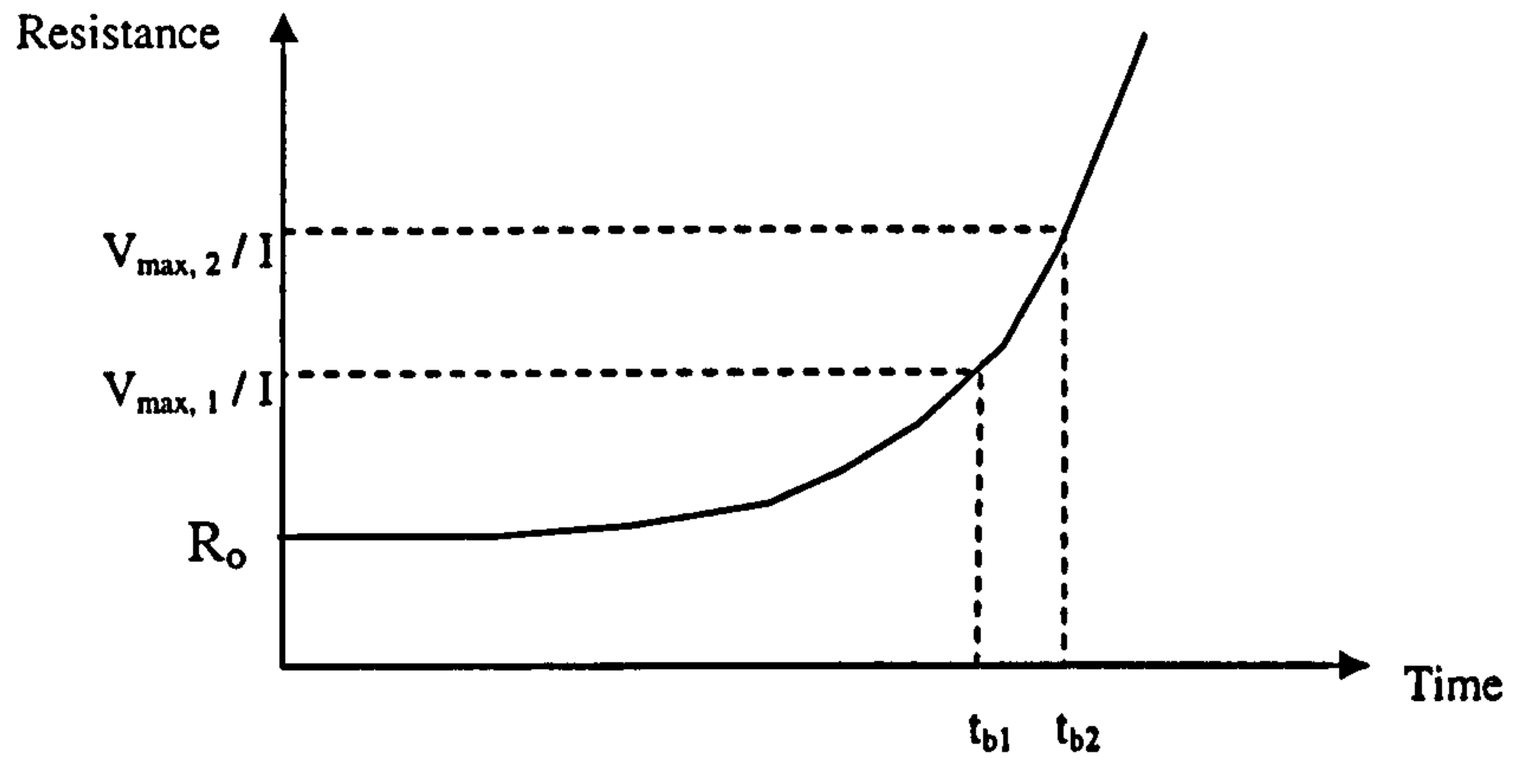


Figure 5.3 Increase in the time over which constant current could be maintained, t_b, by using higher maximum voltage output of the power supply, V_{max}

maintain constant current as resistance increases with time due to electrochemical reaction and desiccation at the anode. When the voltage reaches the maximum voltage output of the power supply, V_{max}, at which point $Resistance > V_{max} / I$, the current cannot be kept constant and will decrease. Figure 5.3 shows the relationship between resistance and time.

In the design process, it is necessary to choose a suitable power supply such that the maximum voltage output can be maintained at a sufficiently high level to provide a constant current for the treatment time. The time over which constant current could be maintained, t_b, increases with the maximum voltage output, V_{max}. However, the resistance during the electroosmotic dewatering process is a function of time and rises at an ever increasing rate so that increasing the maximum voltage output from the power supply, V_{max}, produces progressively less improvement in the time that the current remains constant. It can be seen from Figure 5.3 that constant current cannot be maintained for very long ($t_{b2} - t_{b1}$) by increasing the maximum voltage output of the power supply from $V_{max,1}$ to $V_{max,2}$ once the resistance increases sharply with time. Therefore, an increasingly high power consumption will be required to achieve a longer t_b, which may be uneconomical.

5.3.5 PRESSURE

When a pressure is applied to the sludge, the stress is carried by the water in the pores as well as the solid grains. The increase in pressure within the pore water causes drainage. The rate of drainage depends on the hydraulic permeability of the sludge. However, due to the relatively low hydraulic permeability of sludge, slow seepage occurs and the volume of extracted water by applied pressure is not significant unless very high pressure is applied and even then is limited due to the way in which water is bound to the sludge particles. Besides, from Equation 4.27, it can be seen that the electroosmotic flow is independent of pressure.

In practice, the electroosmotic dewatering process can be enhanced by the application of pressure and increasing the pressure produces a significant overall improvement in the volume of water obtained (Table 4.2). This is attributed to a reduction in air voids within the sludge sample which decreases the electrical resistance. A low rate of increase in resistance during the electroosmotic dewatering process results in a longer time over which the dewatering process remains in constant current dewatering. It also prevents the dewatering process from wasting energy because of high resistance.

5.3.6 TYPE OF ELECTRODES

The principle criterion in the selection of electrodes is that they must be sufficiently electrically conductive. Besides that, the rate of electrochemical reaction taking place at the electrodes also has to be considered in the selection of electrode material. This is because the surface electrical resistivity of the electrode increases when electrochemical reaction occurs and high surface electrical resistivity results in a shorter time over which constant current could be maintained. Therefore, an electrode material with a low rate of electrochemical reaction should be selected in the electroosmotic dewatering process as this not only provides a longer time over which

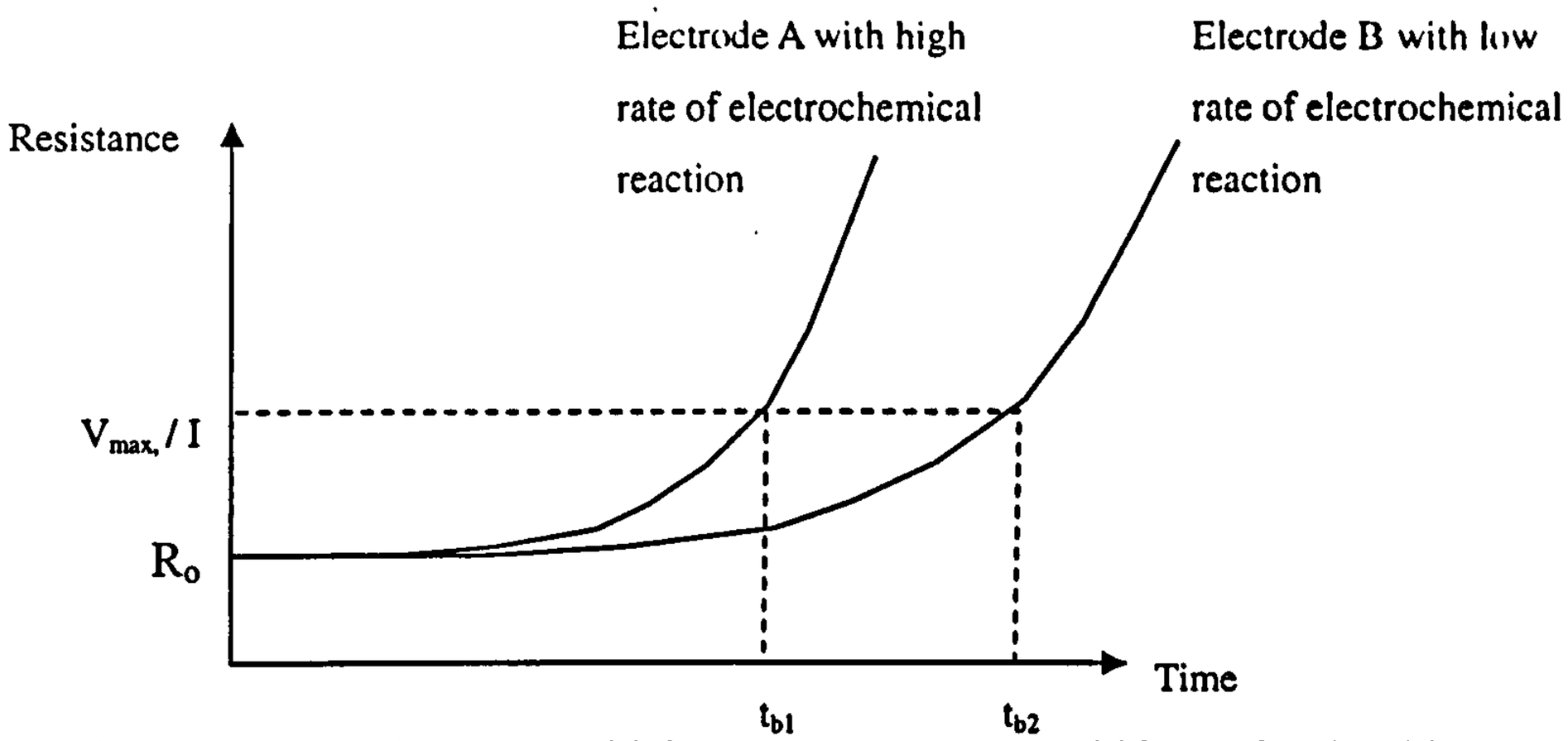


Figure 5.4 Longer time over which constant current could be maintained is obtained by selecting the material with low rate of electrochemical reaction at electrodes.

constant current could be maintained, but also saves electrical energy due to high surface resistance. Figure 5.4 shows that the resistance increases more slowly using an electrode with low electrochemical reaction rate, compared to the electrode with high electrochemical reaction rate. Therefore, the time over which constant current could be maintained, t_b, can be increased by using the electrodes with low rate of electrochemical reaction.

5.4 METHOD TO INCREASE THE TIME OVER WHICH CONSTANT CURRENT COULD BE MAINTAINED

In the electroosmotic dewatering process, the cumulative volume of water extracted has a linear relationship with time when a constant current is maintained. Therefore, it is simple to predict the solid content with time using the design equations derived in Section 5.2. As resistance increases during the process due to electrochemical reactions, the voltage from the power supply has to increase to maintain the constant current according to Ohm's law. When the resistance of the sludge is too high, constant current cannot be maintained by the power supply and the relationship between cumulative volume of extracted water and time is no longer linear. As a

result, the design equations derived in Section 5.2 are not always applicable. Therefore, the time over which constant current could be maintained, t_b, is a key parameter for the design of electroosmotic dewatering with constant current and governs the validity of the design equations. As mentioned in Section 5.3, the length of time over which constant current could be maintained, t_b, is limited by the maximum voltage output of the power supply, V_{max}. Using a power supply with high maximum voltage output can increase the time over which constant current could be maintained, t_b. However, it is uneconomical. In this section, another method to increase the time over which constant current could be maintained, t_b, without increasing the maximum voltage output of the power supply, V_{max}, is discussed.

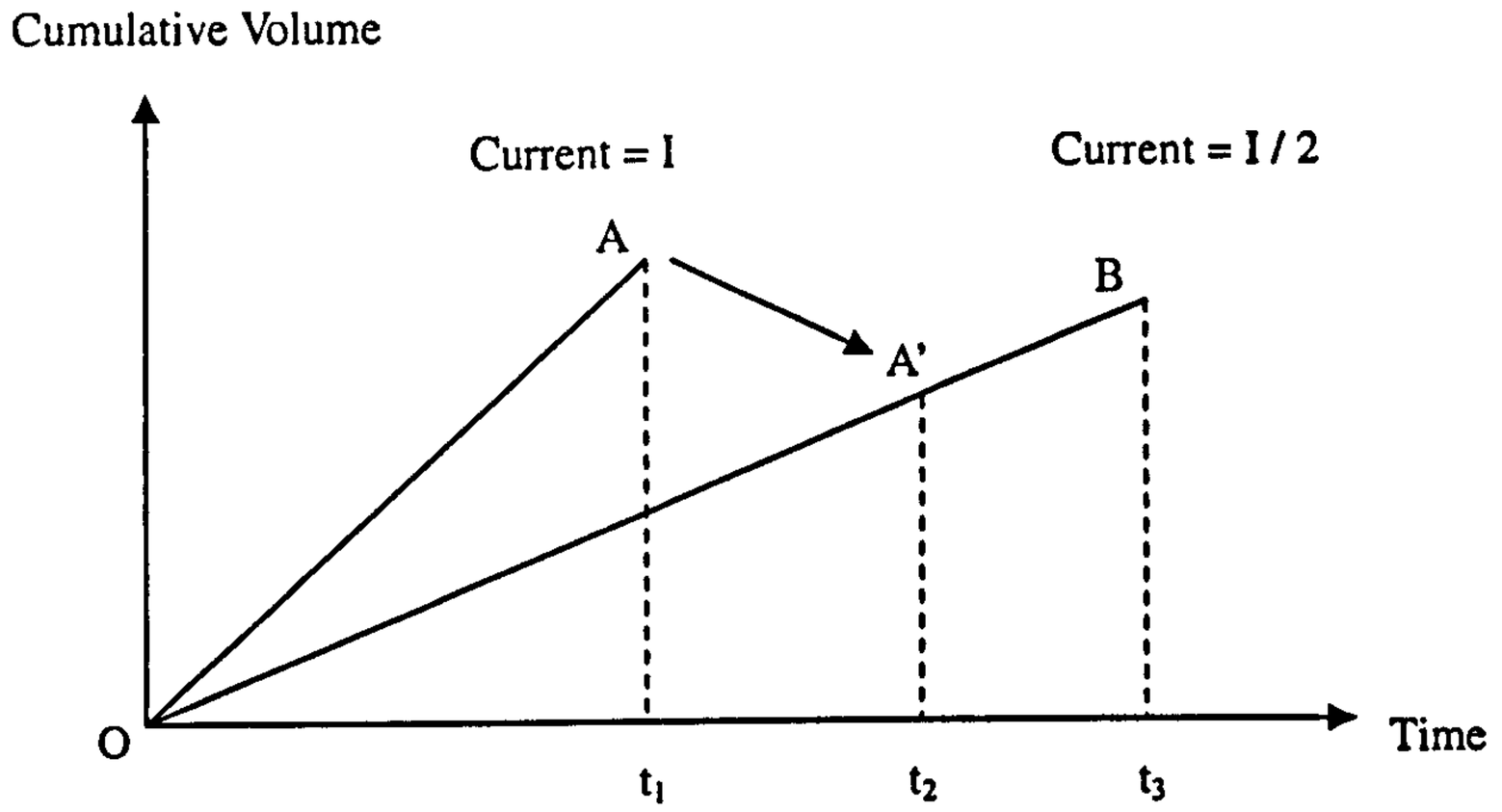
5.4.1 THE CONCEPT OF DEWATERING WITH CONSTANT CURRENT *I* FOLLOWED BY *I* / 2

The method presented in Figure 5.5 is based on varying the applied constant current value to ensure that the design equations are applicable during the dewatering process. At the beginning of the dewatering process, a constant current I is applied and the initial voltage is V_O. During dewatering with a constant current I, the relationship between cumulative volume of extracted water and time is linear as the curve of OA shown in Figure 5.5 c. In order to maintain constant current I, the voltage from the power supply increases with time as resistance increases due to electrochemical reactions. At point A, the voltage reaches the maximum voltage output of the power supply, V_{max}. At this moment, the applied constant current is varied from I to $I / 2$. According to Ohm's law, therefore, the voltage from the power supply is decreased to $V_{max} / 2$ at point A', as shown in Figure 5.5 b. From point A', the sludge is electroosmotically dewatered with a constant current $I / 2$. As the current gradient decreases, the electroosmotic flow rate decreases but remains constant with time. Therefore, the relationship between cumulative volume of extracted water and time

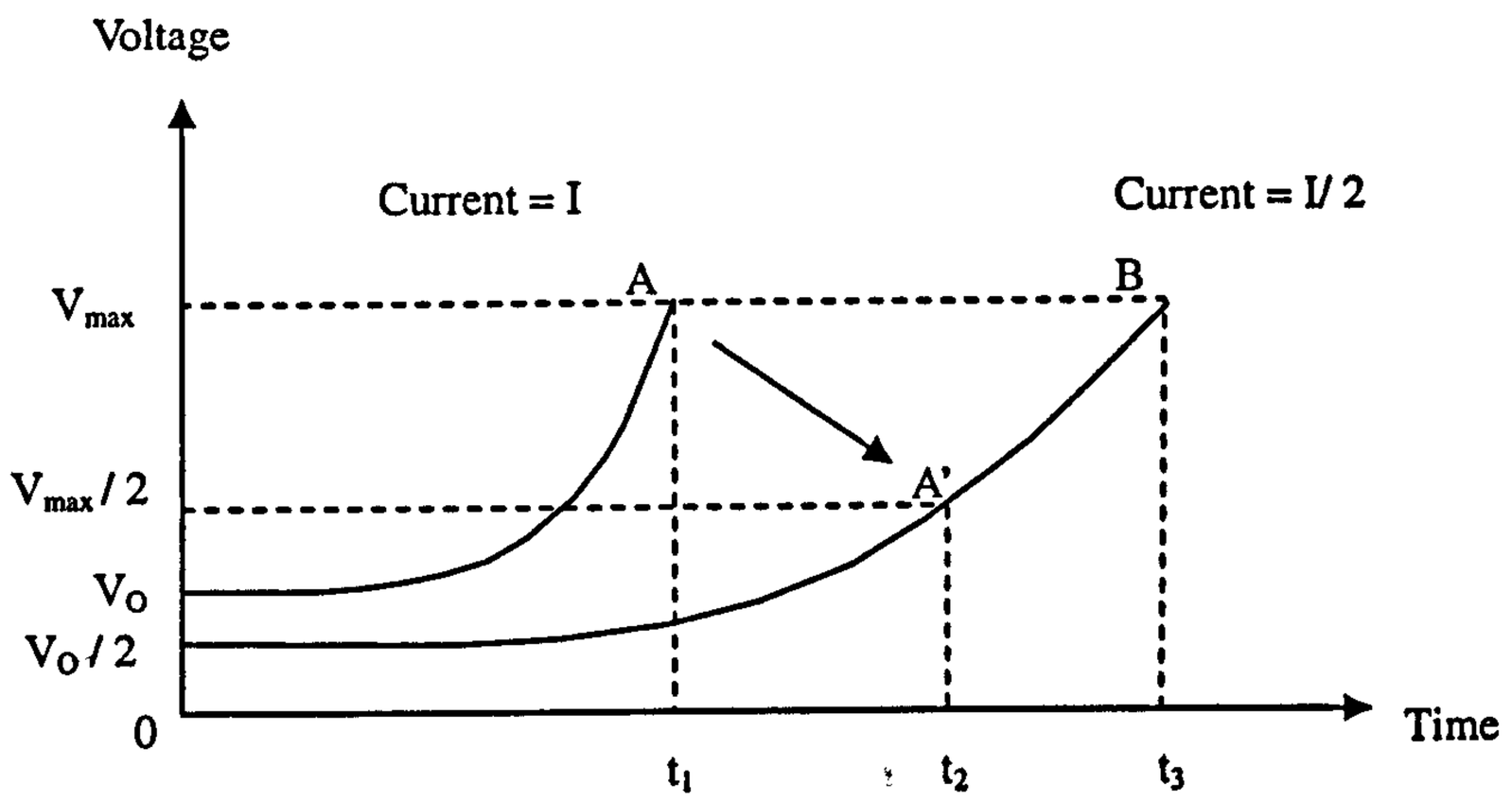
still remains linear as the curve of A'B shown in Figure 5.5c, until the voltage reaches V_{max} at point B. Based on this concept, the time over which constant current could be maintained, t_b, can be increased from t_1 to t_3-t_2+t_1 so that the design equations can be valid for a longer time. Moreover, the required treatment and the final solid content in long-term treatment can be predicted. The limitation of a power supply that cannot maintain a constant current for a long time can also be minimised.

5.4.2 PRODUCING THE DESIGN CURVE FROM EXPERIMENTAL RESULTS

The curve of cumulative volume of extracted water against time for dewatering with a constant current *I* followed by a constant current *I* / 2 (Figure 5.5c) can be predicted from the experimental results of dewatering with constant current *I* and *I* / 2 (Figure 5.5a and Figure 5.5b). Figure 5.5a and Figure 5.5b show the forms of the graphs of cumulative volume against time and voltage against time respectively, based on experimental data for dewatering with constant current *I* and *I* / 2. The predicted curve consists of two linear parts. The first linear part represents initial dewatering with constant current *I* until the voltage reaches the maximum voltage output of the power supply, V_{max}. It is followed by the second linear part which represents secondary dewatering with constant current *I* / 2. As the same constant current *I* is applied initially, the profile of the first part of the predicted curve, as the curve of OA shown in Figure 5.5c, is equal to that of the experimental curve OA as shown in Figure 5.5a. When the voltage reaches the maximum voltage output of the power supply, V_{max}, at time = t_1, the applied current is varied from *I* to *I* / 2. At the moment, the voltage becomes V_{max} / 2. Then, the profile of the second part of the predicted curve as the curve of A'B shown in Figure 5.5c follows the experimental curve A'B as shown in Figure 5.5a, starting from the time = t_2 at which the voltage is V_{max} / 2. This relationship holds true until the voltage reaches the maximum voltage output of the power supply, V_{max}, at time = t_3.



(a)



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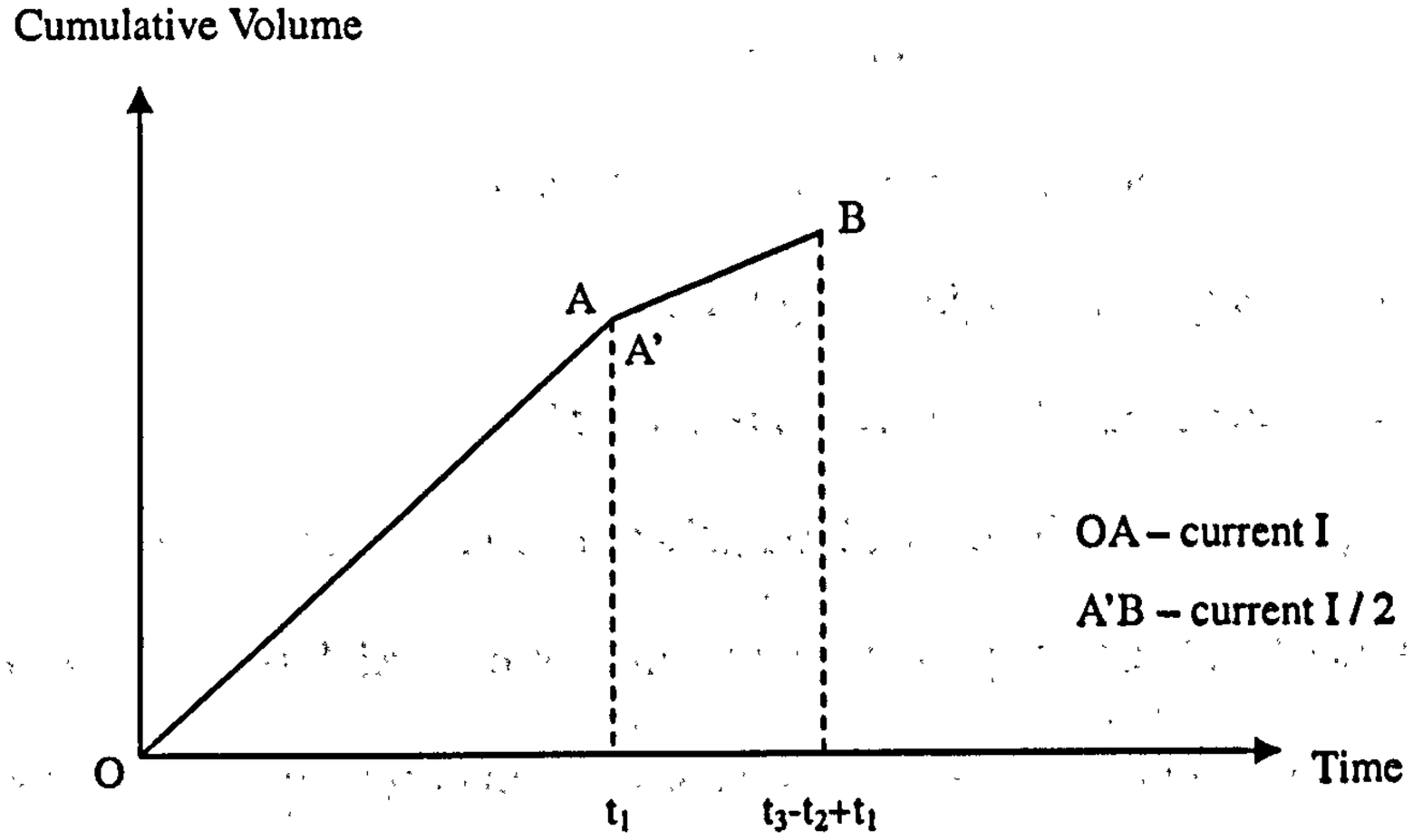


(c)

Figure 5.5 (a) The graphs of cumulative volume against time. (b) The graphs of voltage against time. (c) The cumulative volume-time curve of dewatering with a constant current I followed by a constant current *I* / 2.

In the design process, using the predicted curve and the design equations derived in Section 5.2, the final solid content in a long treatment period can be predicted.

5.5 EXPERIMENTAL PROGRAMME

In this section, a number of experiments was conducted in order to investigate the effects of design parameters on the dewatering process and the time over which constant current could be maintained and demonstrate the validity of the method to increase the time over which constant current could be maintained described in Section 5.4. A similar experimental set-up and same sludge sample were used to that detailed in Section 3.2 and Section3.2.1.1 respectively. However, the procedures were different from those in Chapters 3 and 4. In this section, the experimental procedures will be discussed.

5.5.1 EXPERIMENTAL SERIES 1 – ELECTROOSMOTIC DEWATERING UNDER DIFFERENT CONITIONS

A series of experiments was conducted using the electroosmotic cell with disc electrodes made from perforated copper plates and carbon plates. Initially, the cells were filled with 500g of sludge and 250g of sludge, equating approximately to a sample height of 30mm and 15mm respectively. The experiments were conducted varying the applied pressure to 25kPa, 50kPa and 75kPa while keeping the current constant at 1A and 2A with maximum voltage output of 30V. Experiments were conducted for a total duration of 60 minutes for the current at 2A and 120 minutes for the current at 1A. Readings of the voltage and cumulative volume of extracted water were taken at 60 second intervals for the first 30 minutes, at 5 minute intervals for the next 30 minutes and at 15 minute intervals for the last 60 minutes. Readings of current were taken when the voltage reached a maximum of 30V. After the completion of each test, the solid content of the remaining sludge was measured. The

Table 5.2 Experimental series 1 – Dewatering under different conditions

Test	Electrode	Thickness	Pressure	Current
1	Copper	30mm	25kPa	2A
2	Copper	30mm	50kPa	2A
3	Copper	30mm	75kPa	2A
4	Copper	15mm	25kPa	2A
5	Copper	15mm	50kPa	2A
6	Copper	15mm	75kPa	2A
7	Copper	30mm	25kPa	1A
8	Copper	30mm	50kPa	1A
9	Copper	30mm	75kPa	1A
10	Carbon	30mm	25kPa	2A

Test No. 1 – 6	To investigate the effect of applied pressure
Test No. 2 – 3, 5 – 6	To investigate the effect of sample thickness
Test No. 1 – 3, 7 – 9	To investigate the effect of different currents
Test No. 1, 10	To investigate the effect of different electrode materials

details of the experiments are summarized in Table 5.2.

5.5.2 EXPERIMENTAL SERIES 2 – ELECTROOSMOTIC DEWATERING WITH CONSTANT CURRENT *I* FOLLOWED BY *I* / 2

The experiment was conducted using the electroosmotic cell with copper disc electrodes. The cell was filled with 500g of sludge. A pressure of 75kPa was applied to the piston. Initially, a constant current of 2A was applied to the sludge by a power supply with a maximum voltage output of 30V. When the voltage reached maximum of 30V, a constant current of 1A was subsequently applied to the sludge and maintained until the voltage reached 30V again. During the experiment, readings of

voltage and cumulative volume of extracted water were taken at 60 seconds intervals. After the completion of the test, the solid content of the remaining sludge was measured.

5.6 RESULTS AND DISCUSSION

5.6.1 EXPERIMENTAL SERIES 1 – ELECTROOSMOTIC DEWATERING UNDER DIFFERENT CONITIONS

In this section, the effects of design parameters (pressure, sample thickness, current and electrode materials) on the electroosmotic dewatering process are discussed with the experimental results.

5.6.1.1 EFFECT OF APPLIED PRESSURE

The experimental results for investigating the effect of applied pressure on the dewatering process are shown in Figure 5.6 and Figure 5.7. For 15mm thick sample, the times to maintain constant current, t_b, for applied pressures of 25kPa, 50kPa and 75kPa were 20mins, 24mins and 22mins respectively. For a 30mm thick sample, the times over which constant current could be maintained, t_b, with applied pressures of 25kPa, 50kPa and 75kPa were 20mins, 45mins and 40mins respectively. The results showed the substantial increase in t_b when varying the applied pressure from 25kPa to 50kPa. This may be attributed to the higher pressure compressing the sludge particles and removing air voids within the sludge samples, resulting in a lower rate of increase in resistance. However, compared with 50kPa, the time over which constant current could be maintained, t_b, was shortened when the pressure was increased to 75kPa. This was thought to be because the higher pressure induced a higher hydraulic gradient that caused the water to be extracted more rapidly. As a result, this decreased the moisture content of the sample more rapidly, causing an increase in resistance. Even though the resistance was decreased due to the reduction of air volume by applying

high pressure, the effect of reducing water content was more a significant, resulting in an overall increase in resistance. Overall, an increase in pressure resulted in improvement in the volume of water obtained and was a benefit to the dewatering process.

5.6.1.2 EFFECT OF SAMPLE THICKNESS

The results of the experiments investigating the effect of sample thickness on the dewatering process are shown in Figure 5.8 and Figure 5.9. From the results in Table 5.3, it may be seen that doubling the sample thickness doubles the time to reach the same solid content as predicted in Equation 5.16. It may also be seen that less power is consumed to obtain same solid content in the sludge when the sludge is 15mm thick, compared to the sludge with a thickness of 30mm. The power consumption shown in Table 2 was measured in kWh/kg of extracted water. On the other hand, as shown in Figure 5.8 and Figure 5.9, the electroosmotic flow rate (slope of the graphs) in stage B was almost the same for both sample thicknesses when dewatering with constant current and pressure. This substantiates the argument that electroosmotic flow rate is not affected by the thickness of the sample when current is kept constant as predicted by Equation 5.18.

5.6.1.3 EFFECT OF DIFFERENT CURRENTS

The results of the experiments investigating the effect of different current values on the dewatering process are shown in Figure 5.10 to Figure 5.13. It can be seen from the results that a linear relationship between cumulative volume of extracted water and time was obtained when sludge was dewatered under constant current. The results in Figure 5.10 show that the overall flow rate (electroosmotic + hydraulic) increased substantially with increase in the current from 1A to 2A. Moreover, an increase in the

Table 5.3 Experimental results: Doubling the sample thickness doubles the time to reach the same solid content

Thickness	Pressure	Treatment Time	Volume of collected water	Solid content	Power consumption
30mm	50kPa	20min	92ml	19.6%	0.148 kWh/kg
15mm	50kPa	10min	47ml	19.7%	0.124 kWh/kg
30mm	50kPa	30min	136ml	22.0%	0.149 kWh/kg
15mm	50kPa	15min	68.5ml	22.0%	0.119 kWh/kg
30mm	75kPa	20min	113ml	20.7%	0.125 kWh/kg
15mm	75kPa	10min	55ml	20.5%	0.109 kWh/kg
30mm	75kPa	30min	161ml	23.6%	0.134 kWh/m^3
15mm	75kPa	15min	80ml	23.5%	0.109 kWh/kg

pressure from 25kPa to 75kPa at same current showed an improvement in overall flow rate. Comparing the effect of current and pressure, the improvement of the dewatering efficiency by increasing current is more than that by increasing pressure. Therefore, in the electroosmotic dewatering system, electroosmosis is the main mechanism of water transport and hydraulic flow due to pressure is secondary.

Furthermore, the times to maintain constant current at different currents and pressures are shown in Figure 5.11 to 5.13. For applied pressure of 25kPa, the times to maintain constant, t_b, for applied current of 1A and 2A were 55mins and 20mins respectively. For applied pressure of 50kPa, the times to maintain constant, t_b, for applied current of 1A and 2A were 98mins and 45mins respectively. For applied pressure of 75kPa, the times to maintain constant current, t_b, for applied current of 1A and 2A were 93mins and 40mins respectively. The results show that the higher current resulted in a shorter time over which constant current could be maintained.

This is thought to be because the higher current results in higher solid content more rapidly and more electrochemical reaction taking place, both increasing the resistance more rapidly with time.

5.6.1.4 EFFECT OF DIFFERENT ELECTRODE MATERIALS

The results of the experiments investigating the effect of different electrode materials on the dewatering process are shown in Figure 5.14 and Figure 5.15. The results show that the resistance increased slowly with time when using carbon electrodes whereas the resistance increased more rapidly with time when using copper electrodes. This is because carbon electrodes require $4e^-$ for the oxidation of each carbon atom and copper electrodes require $2e^-$. Therefore, the rate of electrochemical reaction with carbon electrodes is slower than that with copper electrodes. The electrochemical reaction equations are shown below:

Oxidation taking place at the anode:

$$Cu + H_2O \rightarrow CuO + 2H^+ + 2e^- \quad \text{(for copper anode)}$$

$$C + 2H_2O \rightarrow CO_2 + 4H^+ + 4e^- \quad \text{(for carbon anode)}$$

From the results, the time over which constant current could be maintained using copper electrodes was 20mins, as compared to 32mins using carbon electrodes. This was due to rapid rate of electrochemical reaction, which increased the electrical resistance. This resulted in wasting electrical energy for high electrical resistance. Therefore, using carbon electrodes is more economic in power consumption than using copper electrodes.

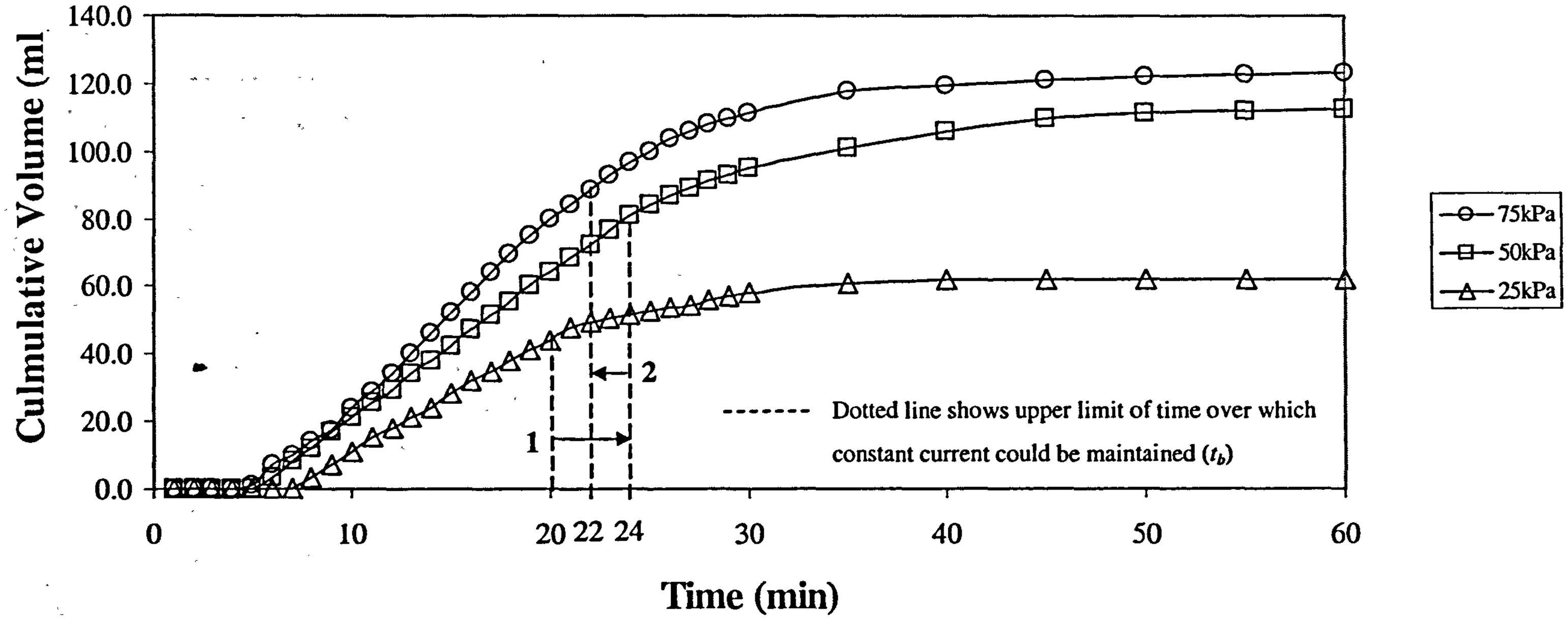
5.6.2 EXPERIMENTAL SERIES 2 – ELECTROOSMOTIC DEWATERING WITH CONSTANT CURRENT *I* FOLLOWED BY *I* / 2

The results of electroosmotic dewatering with constant 2A followed by 1A are shown in Figures 5.18 and 5.19, which are the graphs of voltage against time and cumulative volume of extracted water against time respectively. From the results, it can be seen that there were two linear parts in the graph shown in Figure 5.19. The first linear part represents electroosmotic dewatering with 2A. The second part represents dewatering with 1A. The time over which constant current of 2A could be maintained was 40mins. At that time, the voltage reached the maximum voltage output of 30V. Then, the current value was varied to 1A, resulting decrease in voltage to 15V. The current of 1A was maintained for 26mins following the current of 2A. Therefore, the total time over which constant current could be maintained was 66mins. Compared with dewatering with 2A alone, dewatering with 2A followed by 1A had longer time over which constant current could be maintained so that the dewatering process could be governed by the design equation derived in Section 5.2 for a longer time.

The curve of dewatering with 2A followed by 1A was predicted by the experimental results of dewatering with 1A and 2A. Referring to the results in experimental series 1, the graphs of voltage against time and cumulative volume against time for dewatering with 1A and 2A are shown in Figure 5.16 and Figure 5.17 respectively. The figures show that the times to maintain constant current for 1A and 2A were 93mins and 40mins. Initially, the predicted curve would follow the results of dewatering with 2A until the time = 40mins at which the voltage was 30V. Therefore, the curve of OA as shown in Figure 5.16 and Figure 5.17 is the first linear part of the predicted curve. For dewatering with 1A, the time at which the voltage was 15V was 65mins. Therefore, the second part of the predicted curve would follow the results of

dewatering with 1A from the time at which the voltage was 65mins, until the voltage reached 30V again at time = 93mins. The second part of the predicted curve is shown as the curve of A'B in Figure 5.16 and Figure 5.17. The combination of the curve of OA and A'B is the predicted curve as shown in Figure 5.18 and Figure 5.19. The total time to maintain constant current of the predicted curve was 68mins. Comparing the predicted curve with the experimental results, both curves were almost the same. It is demonstrated that the experimental results comply with the concept of the method to increase the time over which constant current could be maintained described in Section 5.4.

Cumulative Volume of Extracted Water against Time (Different Pressure: Copper + 15mm + 2A)

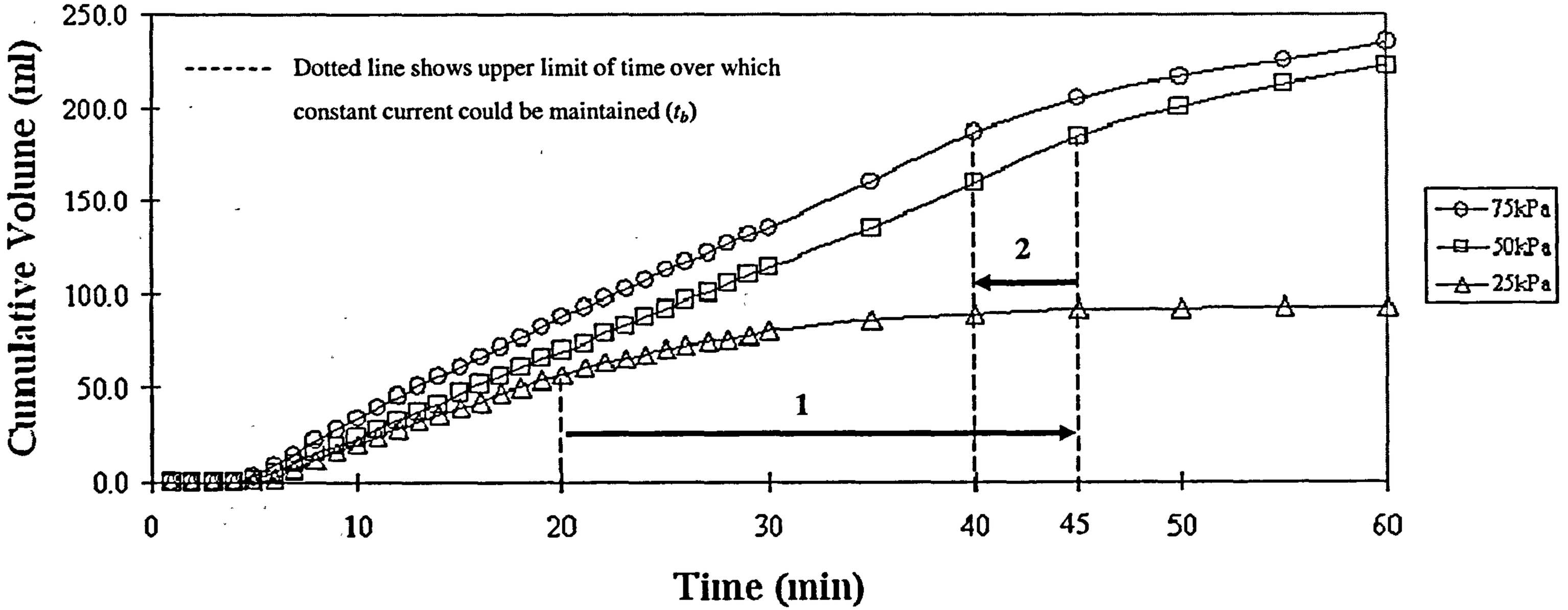


Remark 1: t_b is increased significantly due to low rate of increase in resistance caused by compression

Remark 2: t_b is decreased slightly due to increase in resistance, caused by increase in solid content

Figure 5.6 The experimental results for investigating the effect of applied pressure (sample thickness = 15mm; current = 2A)

Cumulative Volume of Extracted Water against Time (Different Pressure: Copper + 30mm + 2A)



Remark 1: t_b is increased significantly due to low rate of increase in resistance caused by compression

Remark 2: t_b is decreased slightly due to increase in resistance, caused by increase in solid content

Figure 5.7 The experimental results for investigating the effect of applied pressure (sample thickness = 30mm; current = 2A)

Cumulative Volume of Extracted Water against Time (Different Thickness: Copper + 50kPa + 2A)

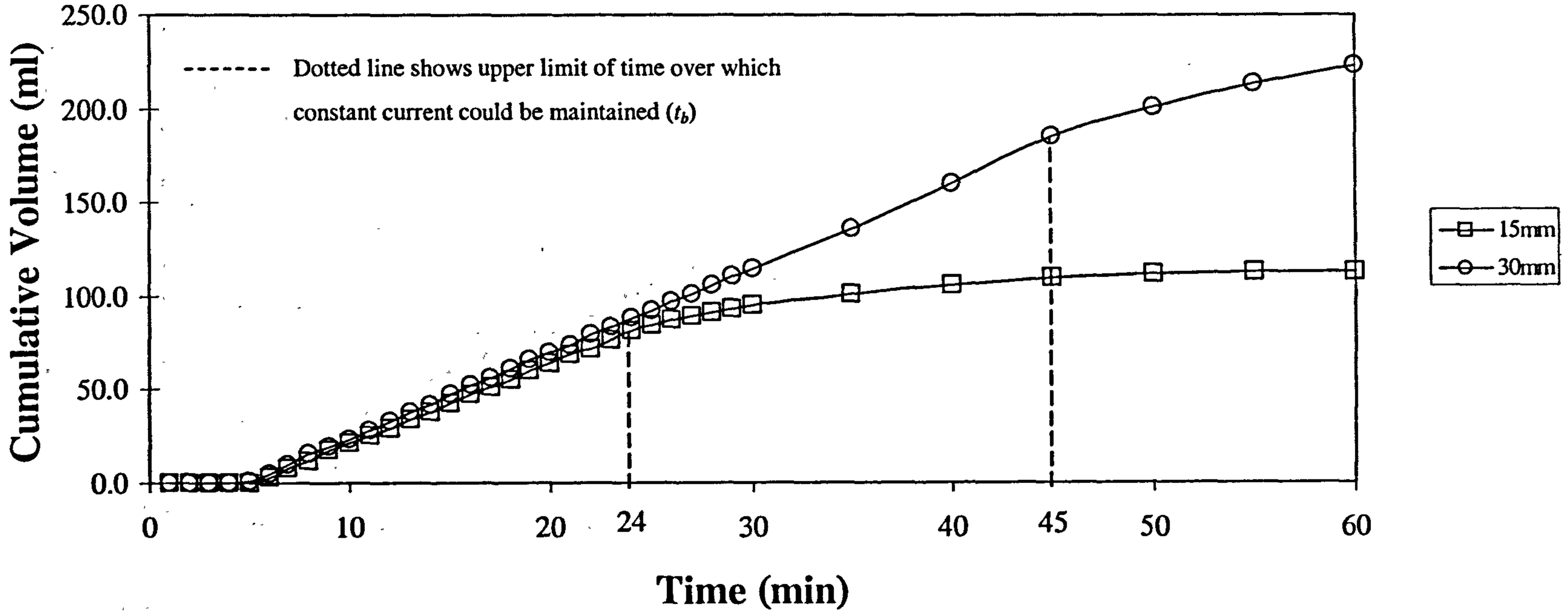


Figure 5.8 The experimental results for investigating the effect of sample thickness (pressure = 50kPa; current = 2A)

Cumulative Volume of Extracted Water against Time (Different Thickness: Copper + 75kPa + 2A)

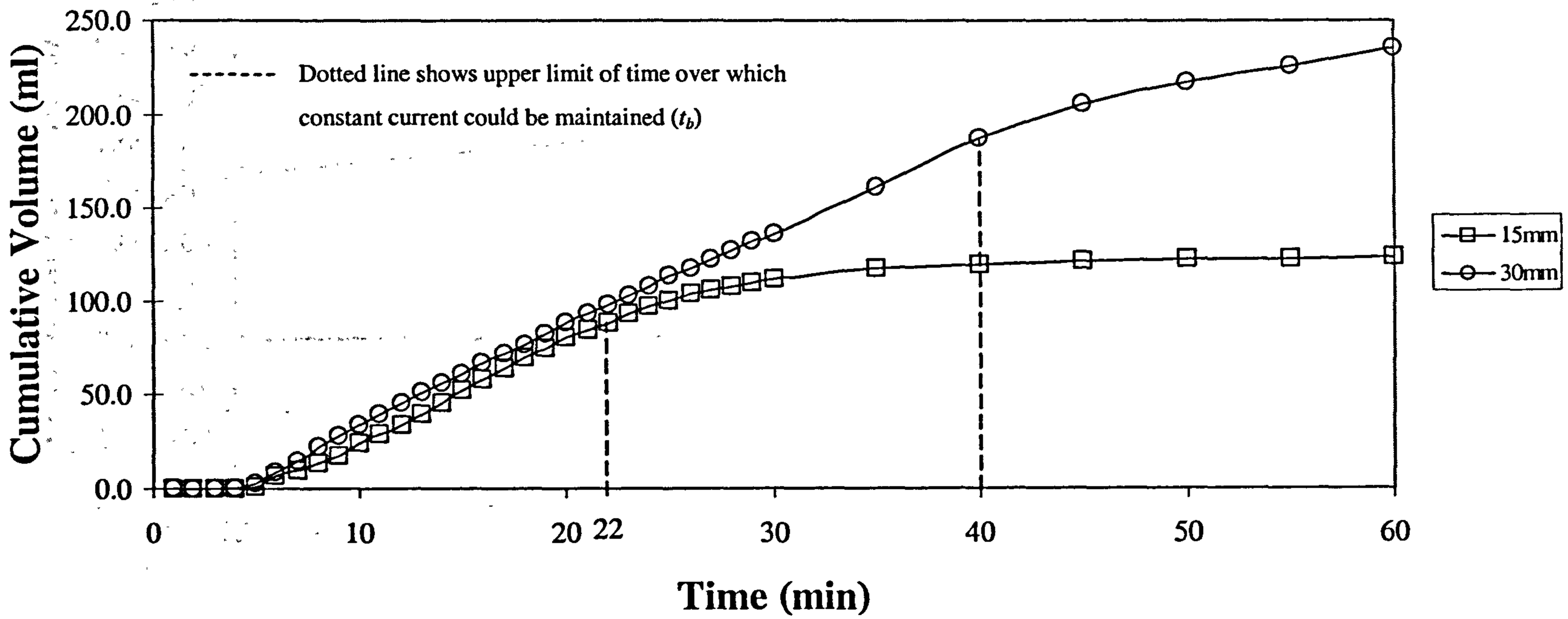


Figure 5.9 The experimental results for investigating the effect of sample thickness (pressure = 75kPa; current = 2A)

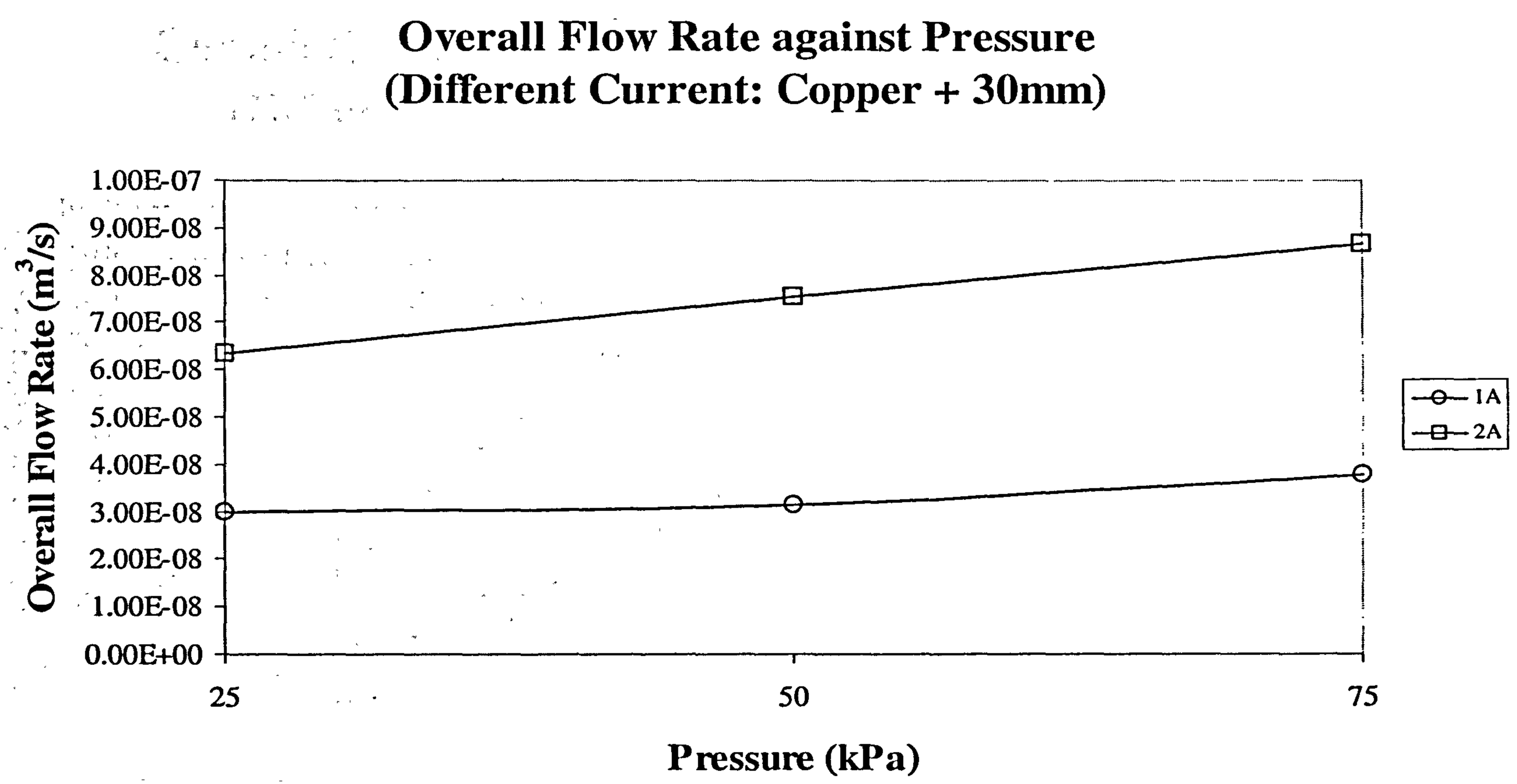


Figure 5.10 The experimental results for investigating the effect of different currents – The graph of overall flow rate against time

Cumulative Volume of Extracted Water against Time (Different Current: Copper + 25kPa + 30mm)

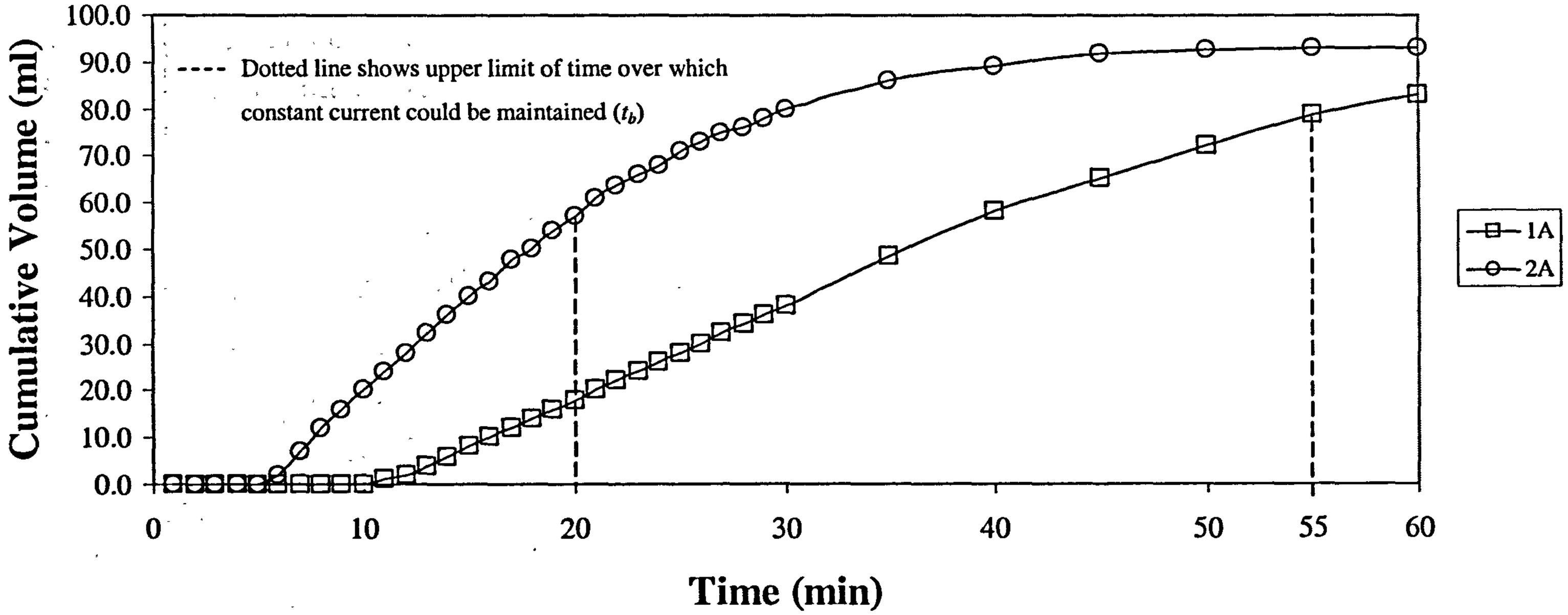


Figure 5.11 The experimental results for investigating the effect of different currents (pressure = 25kPa; sample thickness = 30mm)

Cumulative Volume of Extracted Water against Time (Different Current: Copper + 50kPa + 30mm)

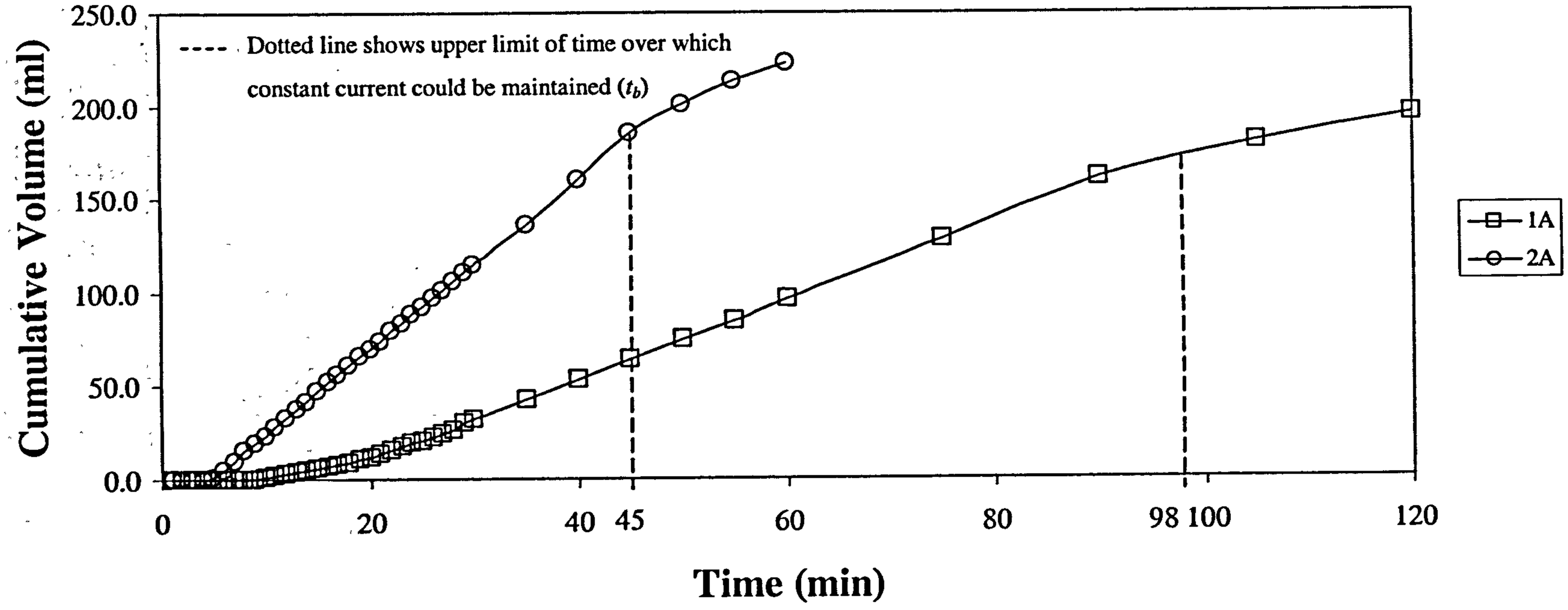


Figure 5.12 The experimental results for investigating the effect of different currents (pressure = 75kPa; sample thickness = 30mm)

Cumulative Volume of Extracted Water against Time (Different Current: Copper + 75kPa + 30mm)

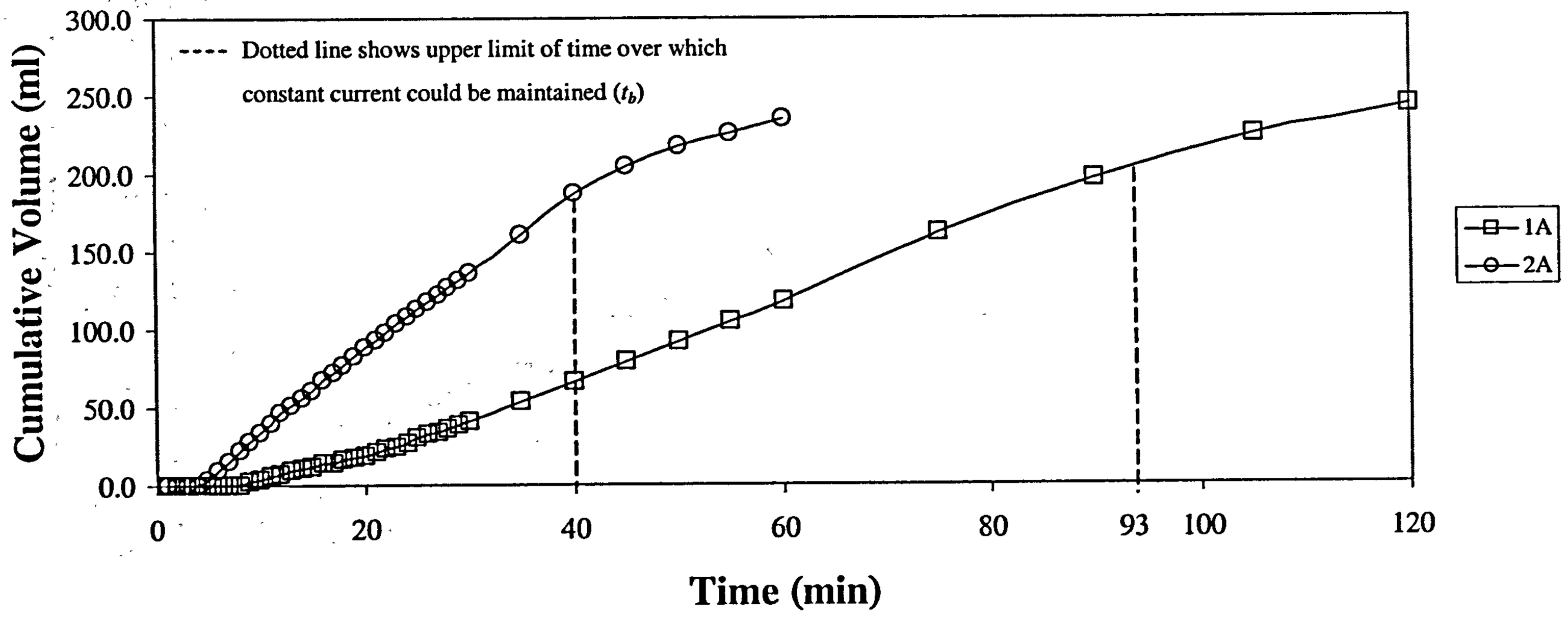


Figure 5.13 The experimental results for investigating the effect of different currents (pressure = 75kPa; sample thickness = 30mm)

Cumulative Volume of Extracted Water against Time (Different Electrode: 25kPa + 2A + 30mm)

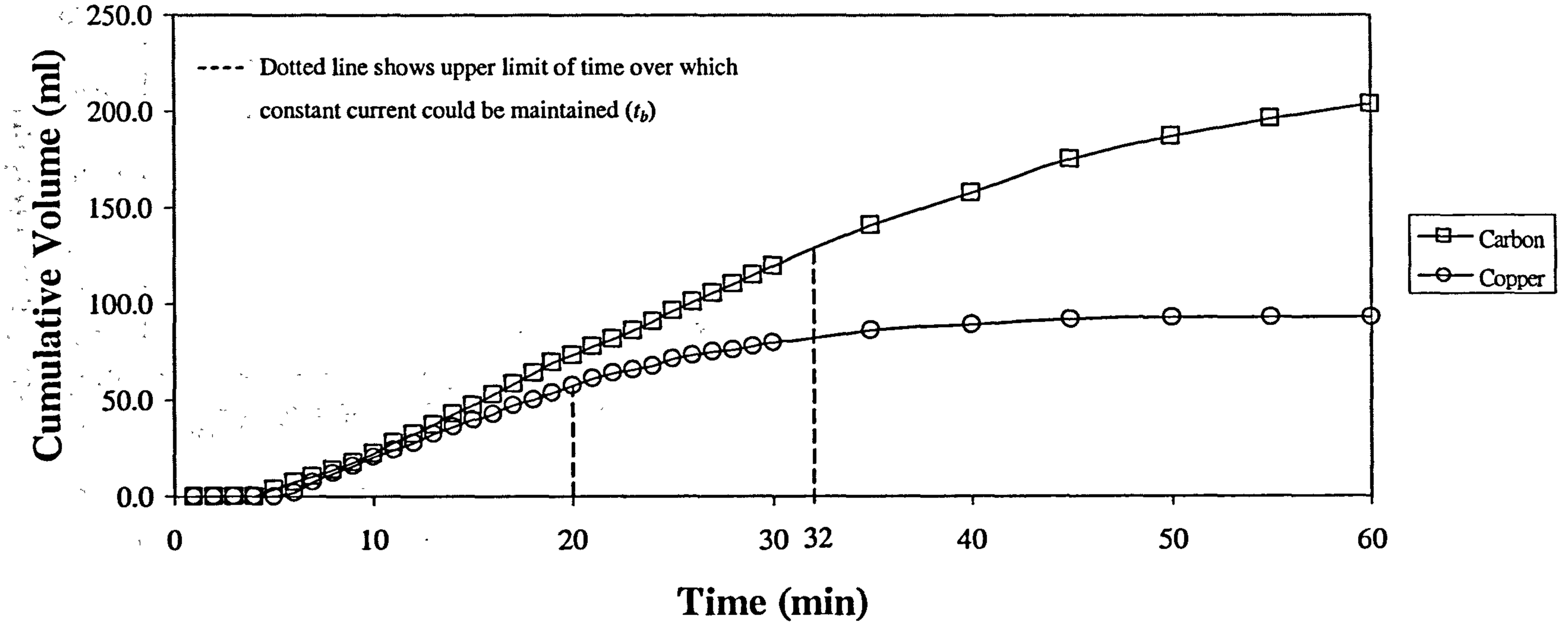


Figure 5.14 The experimental results for investigating the effect of different electrode materials

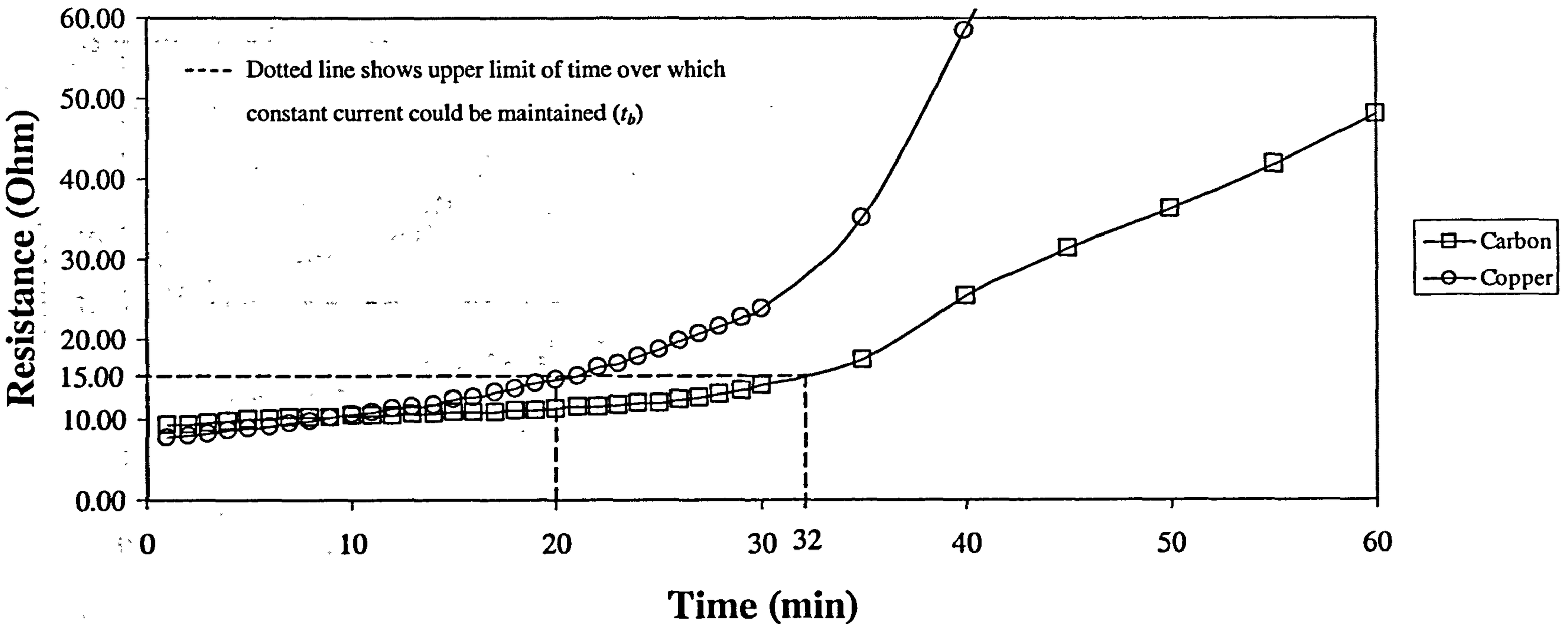
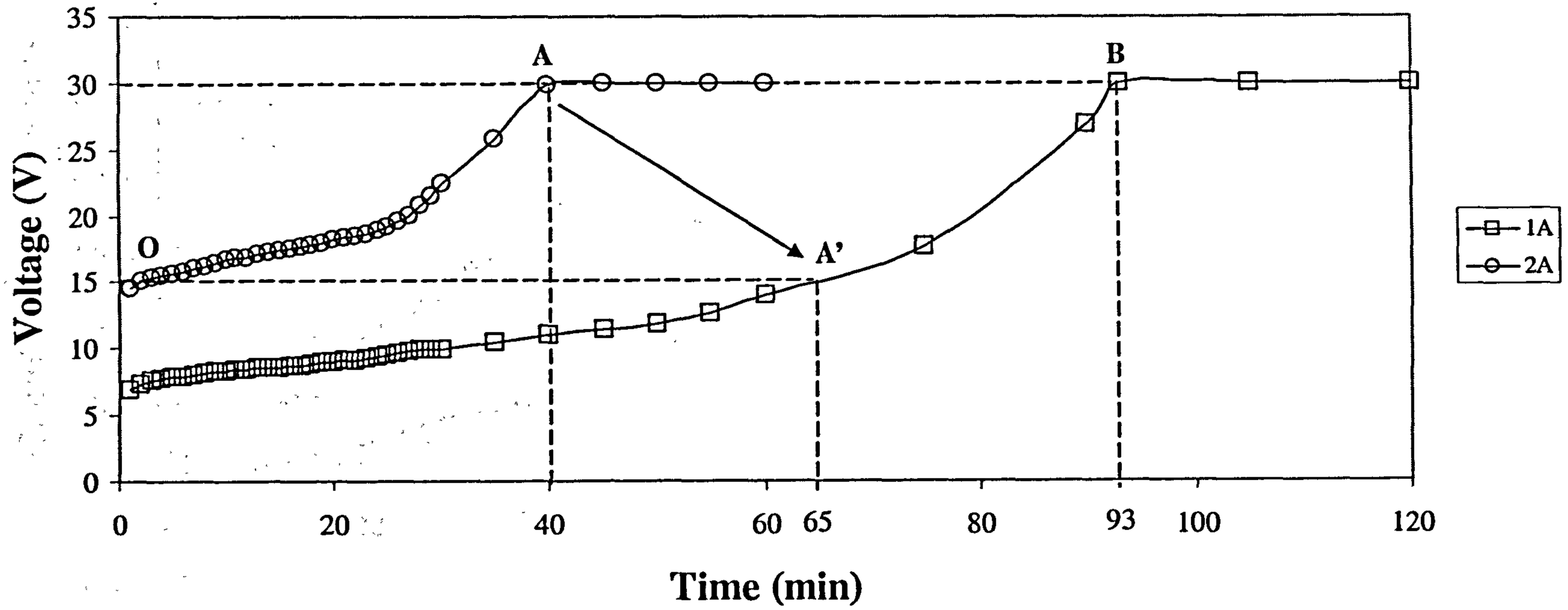


Figure 5.15 The experimental results for investigating the effect of different electrode materials – The graph of resistance against time

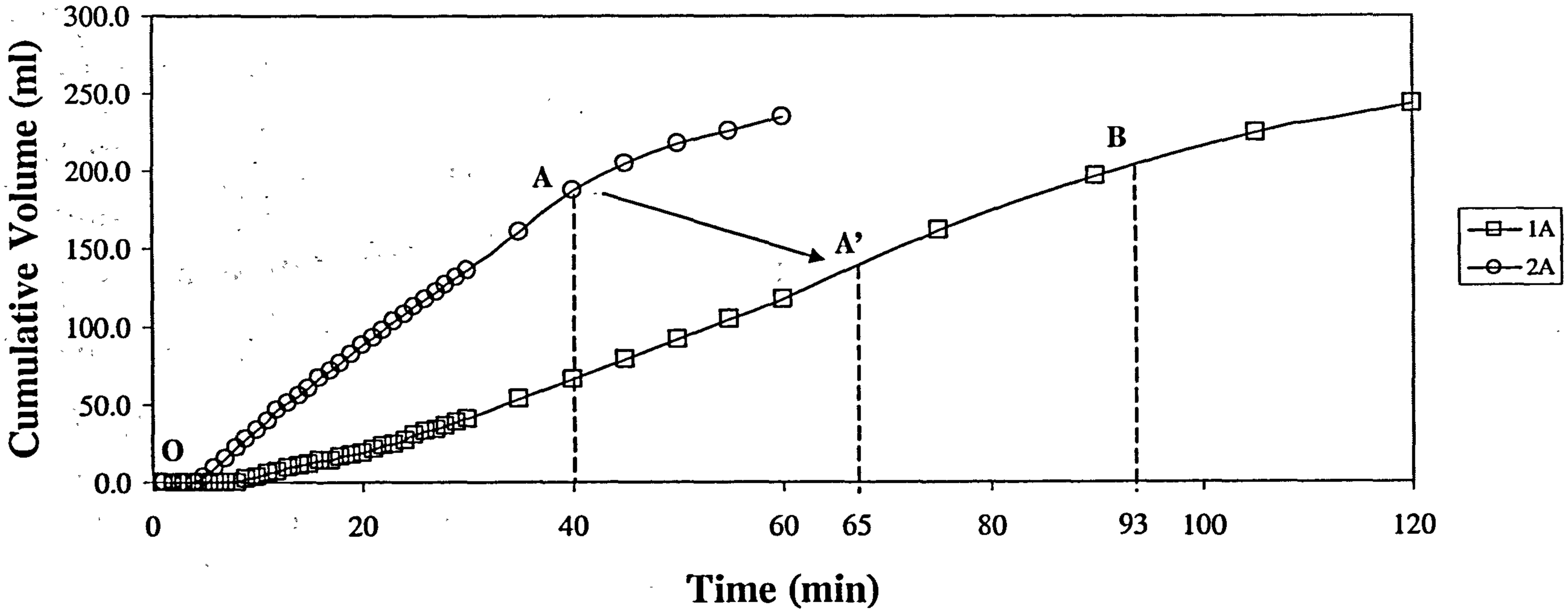
Voltage against Time
(Different Current: Copper + 75kPa + 30mm)



Remark : See Sections 5.41 & 5.42 for explanation of OA and A'B

Figure 5.16 Experimental results of electroosmotic dewatering with 1A and 2A – The graph of voltage against time

Cumulative Volume of Extracted Water against Time (Different Current: Copper + 75kPa + 30mm)



Remark : See Sections 5.41 & 5.42 for explanation of OA and A'B

Figure 5.17 Experimental results of electroosmotic dewatering with 1A and 2A – The graph of cumulative volume against time

Voltage against Time
(Dewatering with 2A followed by 1A)

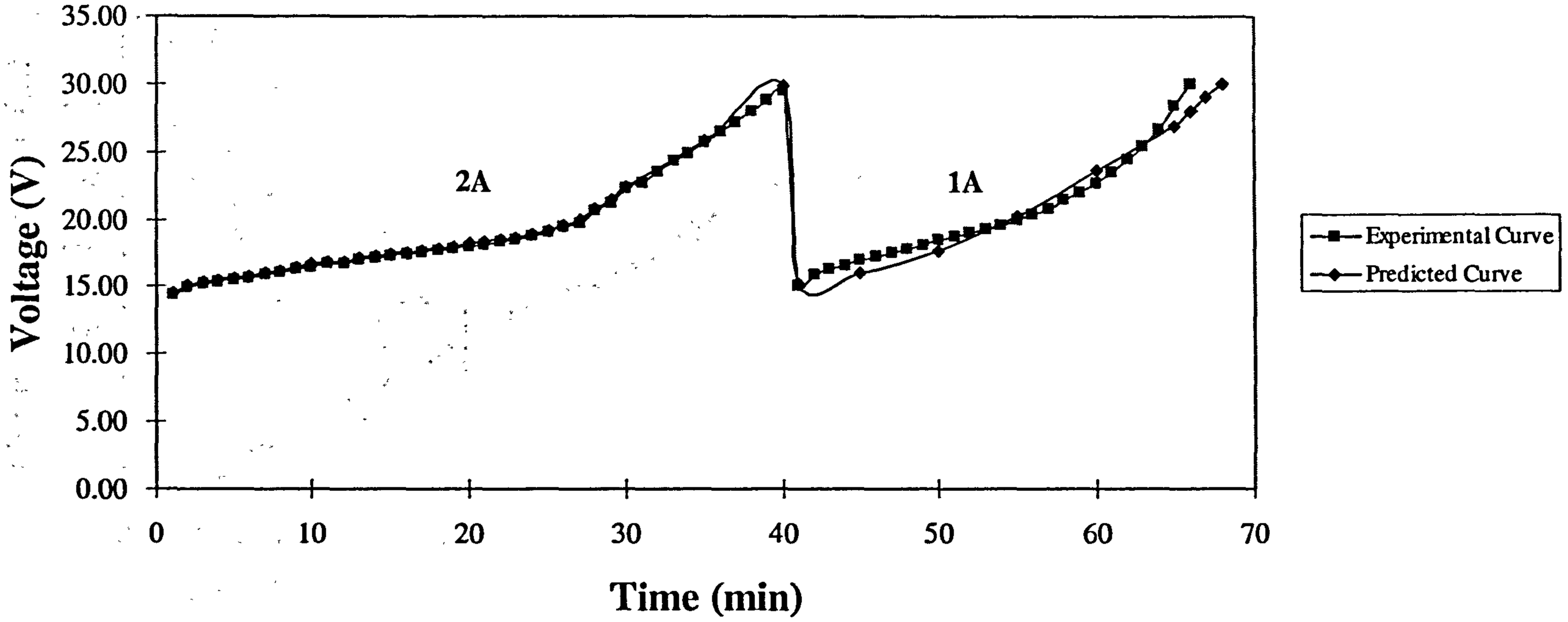


Figure 5.18 The results of experimental series 2 – The graph of voltage against time

Cumulative Volume of Extracted Water against Time (Dewatering with 2A followed by 1A)

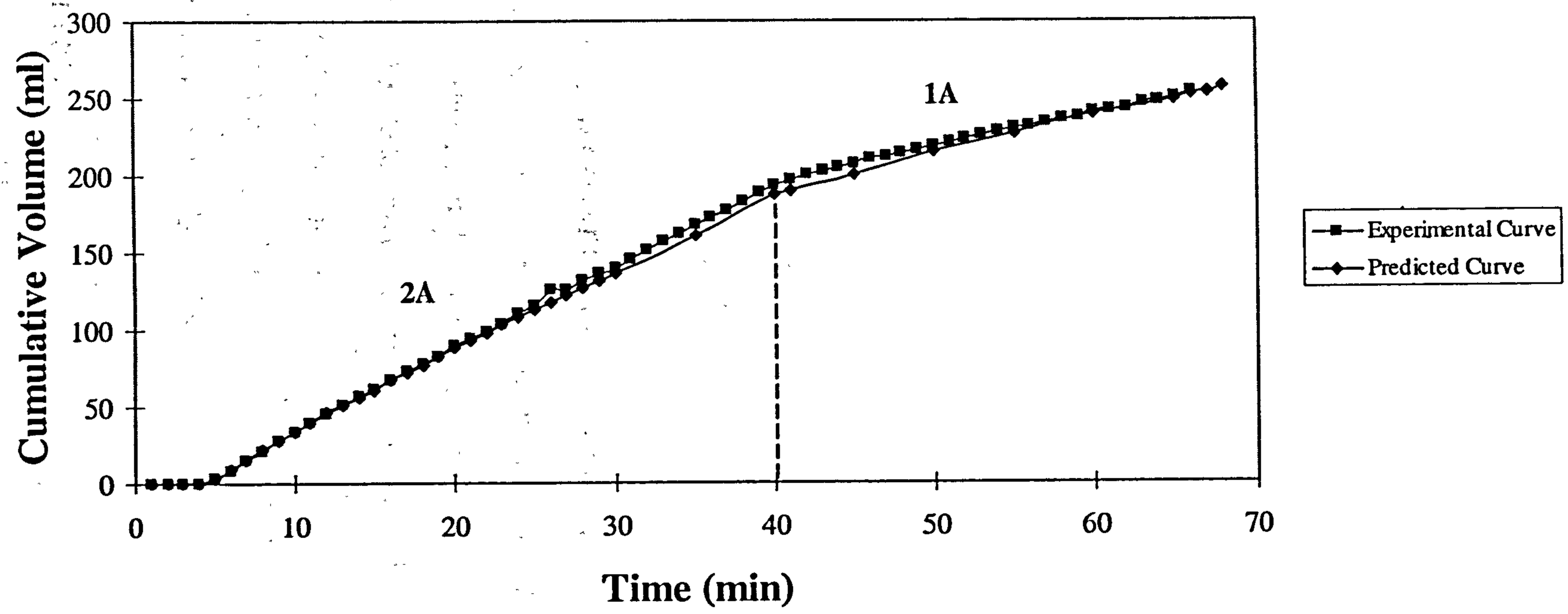


Figure 5.19 The results of experimental series 2 – The graph of cumulative volume against time

5.6.3 DESIGN REQUIREMENTS FOR EACH PARAMETER

For designing an electroosmotic dewatering system under constant current, the design requirements for each parameter are discussed below.

5.6.3.1 SAMPLE THICKNESS

The sample thickness does not affect the electroosmotic flow rate and treatment time. It affects the initial resistance of the sludge only. Therefore, in the design of the electroosmotic dewatering system, the sample thickness should be kept as thin as possible in order to keep the resistance low enough provided that the power supply can maintain constant current.

5.6.3.2 CURRENT

According to Grundl and Michalski (1996), a voltage gradient of 1V/cm is sufficient to produce electroosmotic flow. Based on the concept of dewatering under constant current, the basic requirement of current gradient should not be less than R_O x 1V/cm.

5.6.3.3 TIME OVER WHICH CONSTANT CURRENT COULD BE MAINTAINED

The duration of maintaining constant current governs the validity of design equations derived in Section 5.2. Therefore it should be long enough to make sure the design equations are valid for the whole dewatering process. There are 3 ways to lengthen t_b. They are: (1) increasing the maximum voltage output of the power supply; (2) applying high pressure on the sludge; (3) using electrodes with a low rate of electrochemical reaction and (4) applying I followed by $I/2$

5.6.3.4 POWER SUPPLY

The maximum voltage output of the power supply is related to the time over which constant current could be maintained. It should be maintained sufficiently high

to provide a constant current for the treatment time and must not be less than the initial voltage V_O, which is equal to IR_O.

5.6.3.5 PRESSURE

As the sludge dewaters, the volume of sludge decreases. A minimum pressure that is high enough to compress the sludge and avoid separation between the sludge and the electrodes should be applied.

5.6.3.6 TYPE OF ELECTRODES

The basic requirement of choosing electrodes is that they must be sufficiently electrically conductive. Moreover, the reactivity of the electrode materials to electrolysis should be low because a low rate of electrochemical reaction implies a low rate of increase in resistance during the dewatering process.

5.6.4 DESIGN PROCEDURES OF ELECTROOSMOTIC DEWATERING

The design equations have been derived in Section 5.2 and their relevant design parameters, including sample thickness, current, time over which constant current could be maintained, power supply and pressure, have been discussed in Section 5.3. All the design equations and parameters help to understand the design procedures. The way of designing an electroosmotic dewatering system varies with different needs. It involves either the prediction of (1) the required treatment time to obtain the desired solid content; (2) the final solid content after a particular treatment time; or (3) the current to obtain a particular final solid content within a particular treatment. For all these aspects, there is no need to consider the effect of dimension of sludge (sample thickness, L, and cross-sectional area, A). This is because change of the dimension of sludge affects the initial resistance, R_O, as mentioned in Section 5.3.1. In this section, the design procedures for these aspects are discussed.

5.6.4.1 DESIGN PROCEDURE FOR CALCULATNG TIIE REQUIRED TREATMENT TIME TO OBTAIN DESIRED FINAL SOLID CONTENT

In this case, the desired final solid content is given and the required treatment is unknown and varies with the current. The higher the current, the shorter the treatment time will be. The design procedure for this case (refer to Figure 5.20) is as below:

1. Measure the initial solid content, SD_1;
2. Choose the appropriate current, I;
3. Choose the appropriate applied pressure, type of electrodes and maximum voltage output of the power supply, V_{max};
4. Use the electroosmotic cell with the design parameters chosen in Steps 2 and 3 to determine the electroosmotic permeability, k_e, the time over which constant current could be maintained, t_b; and the initial resistance, R_O;
5. Calculate the required treatment time, t, using Equation 5.12 with the experimental results in Step 4;
6. Compare the required treatment time, t, with the time over which constant current could be maintained, t_b. If the required treatment time is less than the time over which constant current could be maintained ($t < t_b$), the actual required treatment time of the electroosmotic dewatering system will be the required treatment calculated in Step 5. If the required treatment time is larger than the time over which constant current could be maintained ($t > t_b$), go back to Step 2 with applying a constant current of $I / 2$ or go back to Step 3 and increase the maximum voltage output of the power supply, V_{max}, and/or applied pressure and/or choose another material with lower rate of electrochemical reaction as the electrodes in order to increase the time over which constant current could be maintained, t_b.

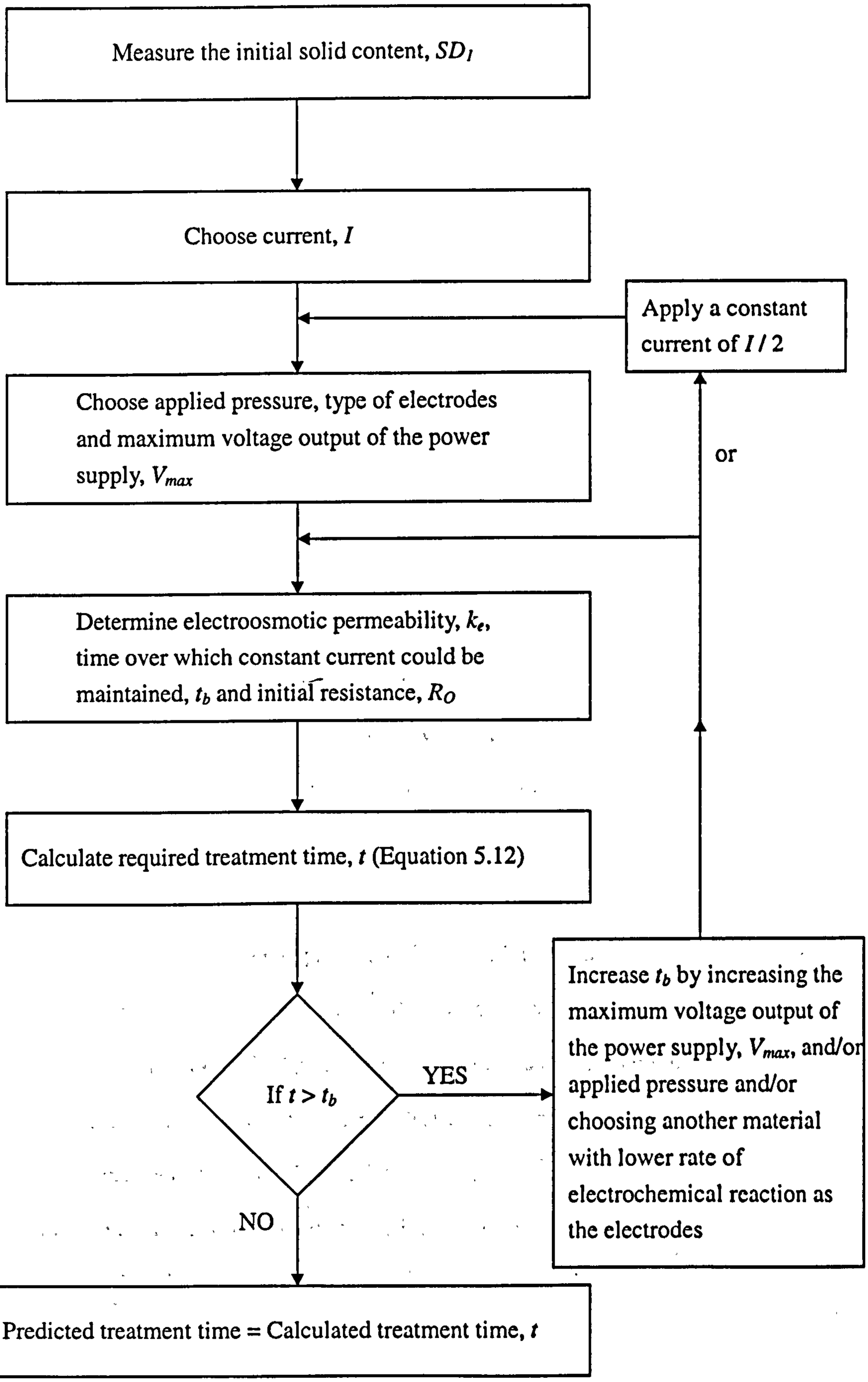


Figure 5.20 Flow chart for the prediction of required treatment time

5.6.4.2 DESIGN PROCEDURE FOR CALCULATING THE FINAL SOLID CONTENT AFTER A PARTICULAR TREATMENT TIME

In this case, the treatment time is given and the final solid content is unknown and varies with the current. The higher the current, the higher final solid content will be. The design procedure for this case (refer to Figure 5.21) is as below:

1. Measure the initial solid content, SD_1;
2. Choose the appropriate current, I;
3. Choose the appropriate applied pressure, type of electrodes and maximum voltage output of the power supply, V_{max};
4. Use the electroosmotic cell with the design parameters chosen in Steps 2 and 3 to determine the electroosmotic permeability, k_e, the time over which constant current could be maintained, t_b and the initial resistance, R_O;
5. Compare the particular treatment time, t, with the time over which constant current could be maintained, t_b. If the particular treatment time is less than the time over which constant current could be maintained ($t < t_b$), go to Step 6. If the required treatment time is larger than the time over which constant current could be maintained ($t > t_b$), go back to Step 2 with applying a constant current of $I / 2$ or go back to Step 3 and increase the maximum voltage output of the power supply, V_{max}, and/or applied pressure and/or choose another material with lower rate of electrochemical reaction as the electrodes in order to increase the time over which constant current could be maintained, t_b;
6. Calculate the final solid content, using Equation 5.13 with the experimental results in Step 4.

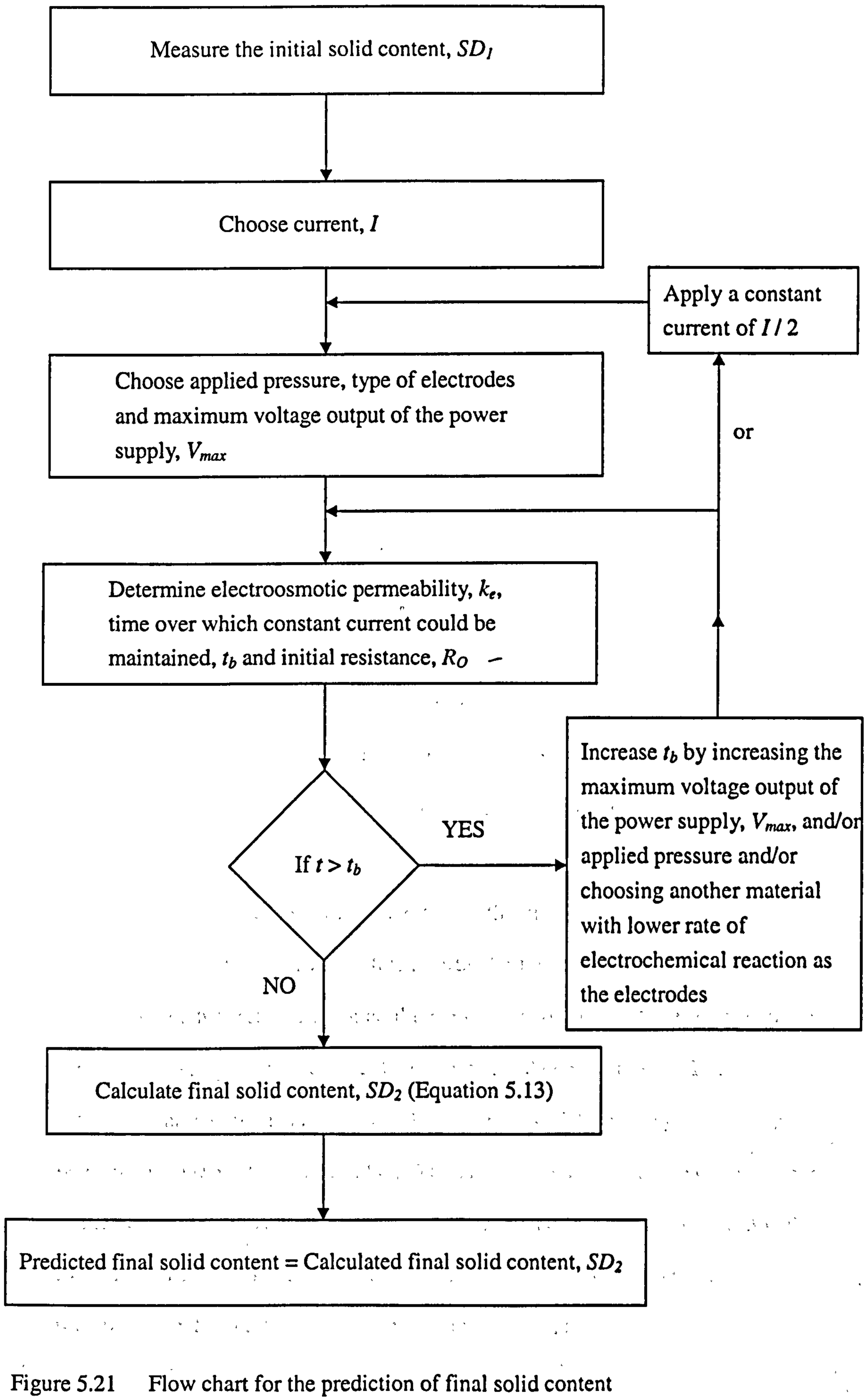


Figure 5.21 Flow chart for the prediction of final solid content

5.6.4.3 DESIGN PROCEDURE FOR CALCULATING TIIE CURRENT TO OBTAIN A PARTICULAR FINAL SOLID CONTENT WITHIN A PARTICULAR TREATMENT TIME

In this case, the treatment time and the final solid content are given and the current is unknown. The design procedure for this case (refer to Figure 5.22) is as below:

1. Measure the initial solid content, SD_1;
2. Choose the trial current, I;
3. Choose the appropriate applied pressure, type of electrodes and maximum voltage output of the power supply, V_{max};
4. Use the electroosmotic cell with the design parameters chosen in Steps 2 and 3 (if redesign, use the current calculated in Step 5) to determine the electroosmotic permeability, k_e and the initial resistance, R_O;
5. Calculate the current, using Equation 5.20 with the experimental results in Step 4;
6. Use the electroosmotic cell with the design parameters chosen in Step 3 and the current calculated in Step 5 to determine the time over which constant current could be maintained, t_b;
7. Compare the particular treatment time, t, with the time over which constant current could be maintained, t_b. If the particular treatment time is less than the time over which constant current could be maintained ($t < t_b$), the current required for the dewatering process will be the current calculated in Step 4. If the required treatment time is larger than the time over which constant current could be maintained ($t > t_b$), go back to Step 3 and increase the maximum voltage output of the power supply, V_{max}, and applied pressure and choose another material with lower rate of electrochemical reaction as the electrodes in order to increase the time over which constant current could be maintained, t_b.

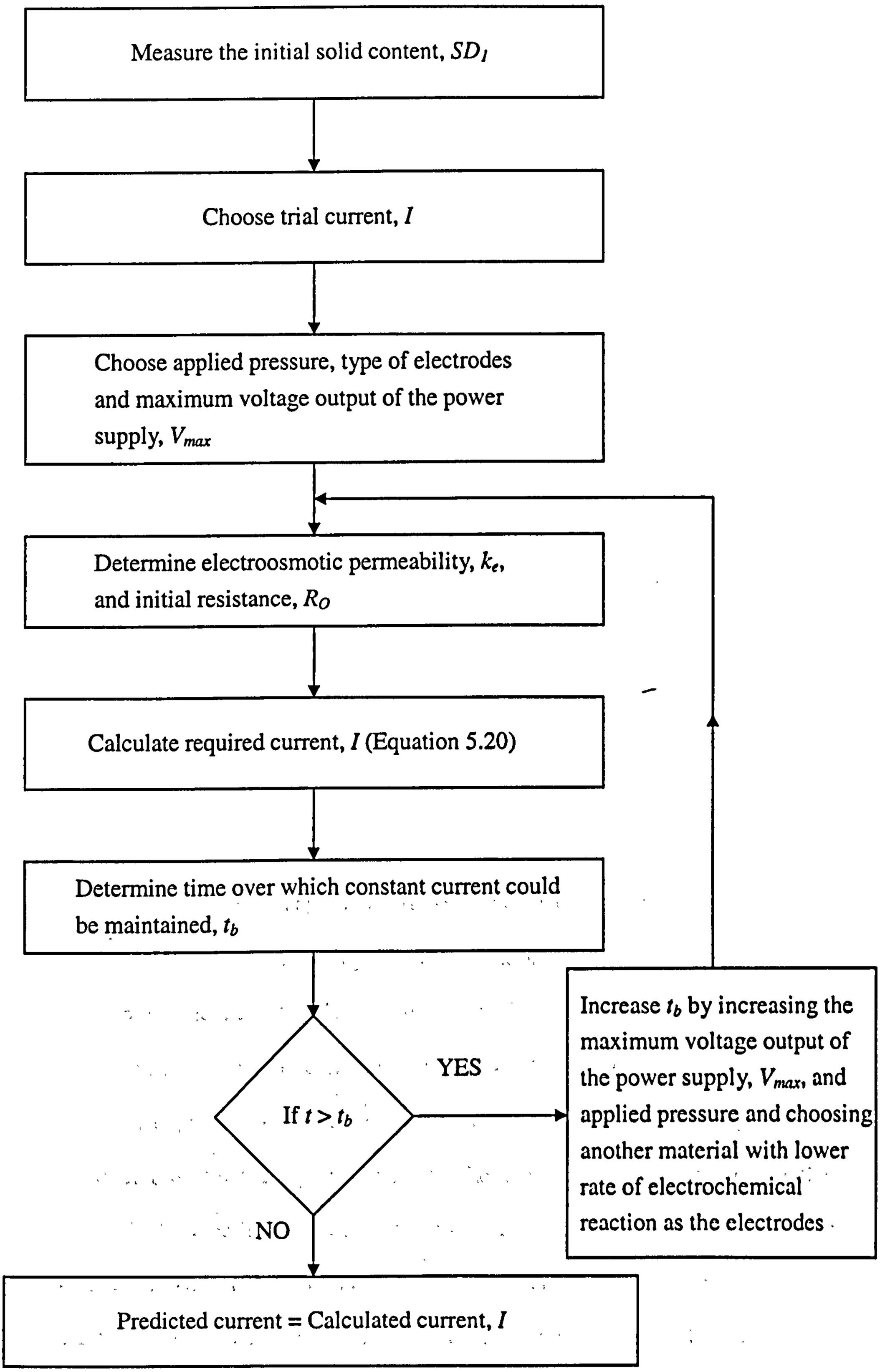


Figure 5.22 Flow chart for the prediction of required current

5.7 CHAPTER SUMMARY

Electroosmotic dewatering of sludge under constant current is a new subject of research and its design concept is different from dewatering under constant voltage. This chapter derives the design equations to calculate the final solid content and treatment time and discusses the theoretical basis for the design parameters, including sample thickness, current, time over which constant current could be maintained, power supply, pressure and type of electrode. The time over which constant current could be maintained, t_b, is a key parameter for the design of electroosmotic dewatering with constant current because the design equations are only valid within t_b. The concept of dewatering with current I followed by $I / 2$ to increase the time over which constant current could be maintained is introduced. The design requirements of each parameter and design procedures are also discussed in this chapter.

The conclusions that may be drawn from the work presented herein may be summarised as follows:

1. When applying the concept of electroosmotic dewatering with constant current, the electroosmotic permeability is independent of sludge cross-sectional area, A, and sample thickness, L. This means that variation of cross-sectional area and sample thickness does not affect the electroosmotic flow rate.
2. The time required to obtain the desired final solid concentration is longer when the thickness of the sludge is increased. Less power is consumed to obtain the same solid content in the sludge when the sample thickness of sludge is smaller, compared to the sludge with higher thickness. Therefore, designing an electroosmotic dewatering system with a small sample thickness has the advantage on economy of power consumption.

3. The electroosmotic flow rate increases with increase in the current, *I*. Therefore, in an electroosmotic dewatering system, higher current results in more water being extracted and saving time to obtain the desired final solid concentration.

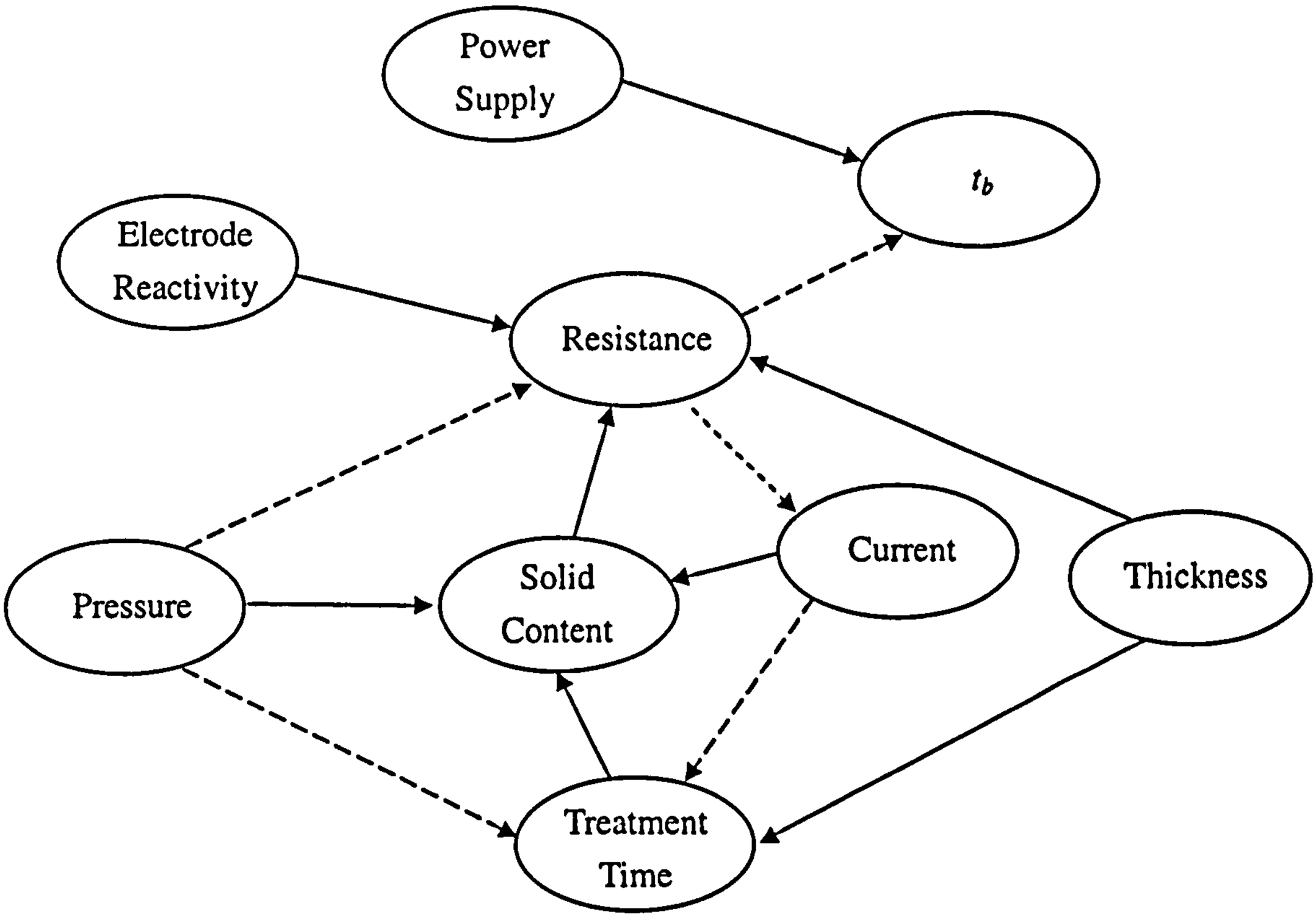
4. An increase in pressure resulted in improvement in the volume of water obtained. This is because it increases the overall flow rate due to a high hydraulic gradient. It also removes air voids resulting in a low rate of increase in resistance during the dewatering process. Therefore, it prevents the dewatering process from wasting energy because of high resistance.

5. The time over which constant current could be maintained, t_b, increases with the maximum voltage output, V_{max}. Therefore, a constant electroosmotic flow rate can be kept for longer when using a power supply with high voltage output. It is helpful for the design of an electroosmotic dewatering process to have a long lasting constant electroosmotic flow rate.

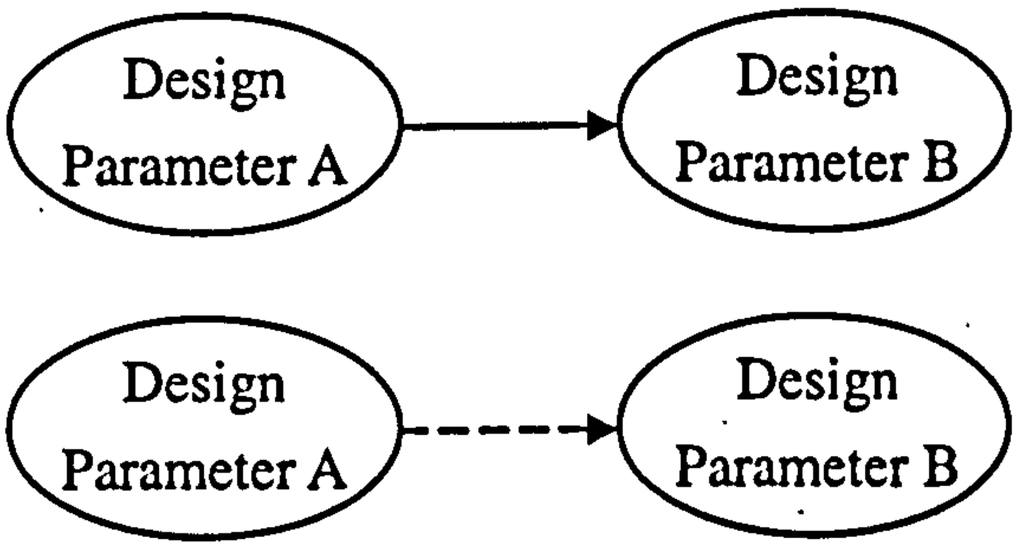
6. Using carbon electrodes yields a longer time over which constant current could be maintained and is more economic in power consumption than using copper electrodes. Therefore, reducing the reactivity of the conducting elements within the press will enhance the overall efficiency of the process as well as its life expectancy.

7. Using the method of dewatering with current *I* followed by *I* / 2 can increase t_b. Therefore, the design equations can be valid for a longer time. The design curve of dewatering with current *I* followed by *I* / 2 can be predicted by the experimental results of dewatering with *I* and *I* / 2.

From the experimental results, it is shown that the design parameters affect each other. Summarising the experimental results, Figure 5.23 shows the relationships between the design parameters.



Legends:



For example:

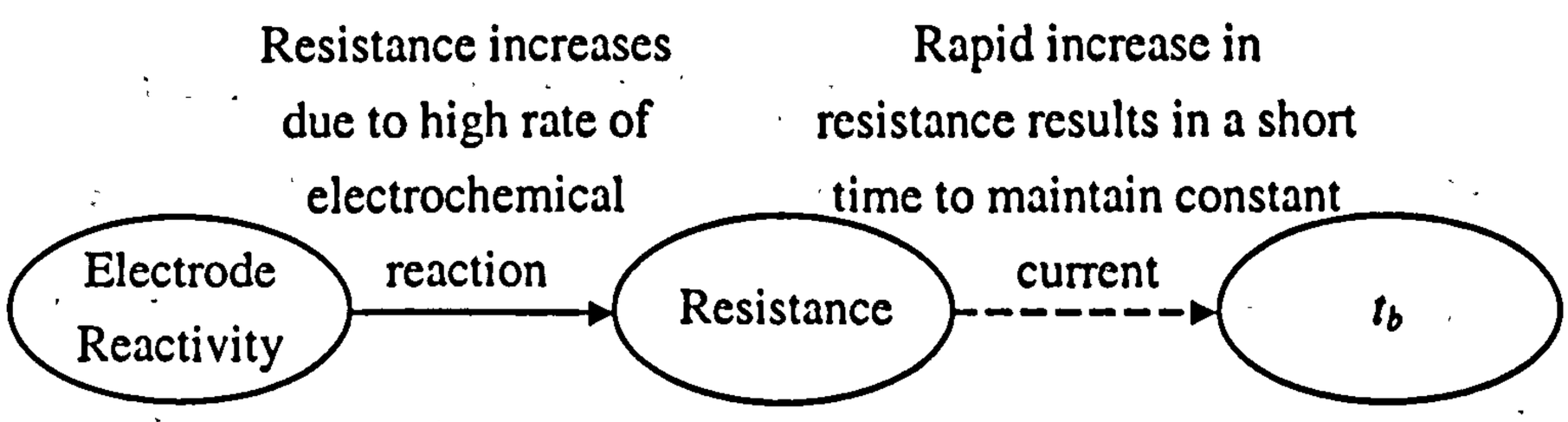


Figure 5.23 Relationships between design parameters

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

6.1 CONCLUSIONS

Every day, wastewater treatment plants product a huge quantity of sludge which has to be transported and disposed of. In order to lower the cost of transportation and disposal, the sludge has to be dried out as much as possible before disposal. However, due to the physical and chemical properties of sludge, removal of water from sludge cannot be easily carried out by conventional dewatering techniques based on mechanical compression. The disposal of sludge is therefore extremely expensive and is becoming a problem facing the whole of the industrialized world.

Electroosmotic dewatering is a novel technique to dewater sludge. Electroosmosis, which is one of the electrokinetic phenomena, is the movement of water under the influence of a direct current electric field. According to the Helmholtz-Smoluchowski theory, electroosmotic flow is a function of voltage gradient and zeta potential and is independent of pore size. The electroosmotic dewatering rate is substantial when dewatering low hydraulic permeability sludge. Moreover, electroosmotic dewatering consumes a relatively low amount of energy when compared to thermal drying. However, electrochemical reactions occur during the dewatering process. Gases are generated at the electrodes and pH changes near the electrodes, resulting in reduced dewatering efficiency by increasing electrical resistance and changing zeta potential respectively. As shown in Chapter 2, many researchers have reported that electroosmotic dewatering of sludge is more efficient than conventional hydraulically driven methods and the dewatering rate can be enhanced by the combination of electric

field and pressure. The positive effect of electroosmotic dewatering of sludge has been known for several years. However, this technology has not yet been successfully applied in industry. This is because there are several technological barriers to the commercial exploitation of this technology that are yet to be resolved. One of these barriers is a scientifically robust design methodology.

In Chapter 3, a number of experiments with different sludge samples were conducted by using the electroosmotic cell to evaluate the feasibility of electroosmotic dewatering of sludge and determine the electroosmotic dewatering efficiency in terms of dewatering rate, energy consumption and final solid content of treated sludge. The experimental results show that a higher final solid content could be obtained and dewatering rate of sludge could be enhanced by the application of electricity, compared to the application of compression. Moreover, the energy consumption for electroosmotic dewatering of sludge was found to be economic, compared to thermal drying. It concludes that the application of electroosmotic dewatering of sludge wastewater treatment is feasible. The experimental results also show that electrical resistance increased and current decreased with time during the dewatering process with constant voltage. Increased resistance, which was mainly caused by electrochemical reactions and desiccation, affected the voltage drawn to generate electroosmotic flow so that electroosmotic flow rate decreased with time. Therefore, the voltage gradient applied to the sludge to generate the electroosmotic flow is not constant and decreases with time even though a constant voltage from power supply is applied to the sludge.

As the electroosmotic flow rate varied with time under constant voltage supply, using Helmholtz-Smoluchowski equation with the assumptions of no electrochemical reaction and constant electroosmotic permeability to predict the dewatering process is not valid. Development of a more robust design framework for electroosmotic dewatering of

sludge is therefore necessary. In Chapter 4, an integrating framework for the design of electrokinetically enhanced dewatering of sludge was developed, founded on the mathematics of simple electrical circuits and demonstrated by laboratory experimentation. The derived equations and experimental results showed that electroosmotic flow rate decreases with time when dewatering with constant voltage and is constant when dewatering with constant current. It concludes that electroosmotic dewateing of sludge with constant current not only enhances the sludge dewatering efficiency, but also has the advantage of simplifying design procedures over those required for electroosmotic dewatering of sludge using constant voltage. This is because the electroosmotic dewatering with constant current can produce a linear relationship between flow and time. For the purpose of simplifying the design process, it is suggested that dewatering of sludge should be achieved by maintaining constant current, instead of constant voltage.

Traditionally, electroosmotic dewatering is achieved by maintaining constant voltage. Therefore, electroosmotic dewatering of sludge under constant current is a new subject for research. In Chapter 5, the design parameters for dewatering with constant current, including sample thickness, applied current, time to maintain constant current, power supply, applied pressure and type of electrodes, were discussed and the design equations for prediction of the final solid concentration of sludge and treatment were derived. Besides, the design requirements for each parameter and design procedures were also discussed. It concludes that the time to maintain constant current, t_b, is a key parameter for the design of an electroosmotic dewatering system under constant current. This is because the design equations are only valid when constant current is maintained. A method to increase the time to maintain constant current, based on the concept of dewatering with current I followed by $I / 2$, was introduced. A number of experiments were conducted in order to investigate the effects of design parameters on the

electroosmotic dewatering process with constant current and the time to maintain constant current. The validity of the concept of dewatering with current *I* followed by *I* / 2 was demonstrated. The following conclusions have been drawn from the work presented in Chapter 5:

1. When applying the concept of electroosmotic dewatering with constant current, the electroosmotic permeability is independent of sludge cross-sectional area, *A*, and sample thickness, *L*. This means that variation of cross-sectional area and sample thickness does not affect the electroosmotic flow rate.
2. The time required to obtain the desired final solid concentration is longer when the thickness of the sludge is increased. Less power is consumed to obtain the same solid content in the sludge when the sample thickness of sludge is smaller, compared to the sludge with higher thickness. Therefore, designing an electroosmotic dewatering system with a small sample thickness has the advantage on economy of power consumption.
3. The electroosmotic flow rate increases with increase in the current, *I*. Therefore, in an electroosmotic dewatering system, higher current results in more water being extracted and saving time to obtain the desired final solid concentration.
4. An increase in pressure resulted in improvement in the volume of water obtained. This is because it increases the overall flow rate due to a high hydraulic gradient. It also removes air voids resulting in a low rate of increase in resistance during the dewatering process. Therefore, it prevents the dewatering process from wasting energy because of high resistance.
5. The time over which constant current could be maintained, t_b, increases with the maximum voltage output, V_{max}. Therefore, a constant electroosmotic flow rate can be kept for longer when using a power supply with high voltage output.

It is helpful for the design of an electroosmotic dewatering process to have a long lasting constant electroosmotic flow rate.

6. Using carbon electrodes is more economic in power consumption than using copper electrodes. Therefore, reducing the reactivity of the conducting elements within the press will enhance the overall efficiency of the process as well as its life expectancy.

7. Using the method of dewatering with current I followed by $I / 2$ can increase t_b. Therefore, it can prolong the time to maintain constant electroosmotic flow rate. The design curve of dewatering with current I followed by $I / 2$ can be predicted by the experimental results of dewatering with I and $I / 2$.

Overall, this research achieved the aim and objectives as stated in Section 1.2.

6.2 RECOMMENDATIONS

There are many issues which have not been covered in this research. In order to improve the electroosmotic dewatering process, some recommendations for further studies are listed as follows:

1. From the experimental results, it was observed that the electrical resistance increased rapidly with time. This was largely due to the occurrence of electrochemical reactions. Experiments should be conducted to examine the effects of electrochemical reactions, such as corrosion, change in pH and gas generation, during electroosmotic dewatering with constant current and then determine preventive measures.
2. As the maximum voltage output of the power supply was 30V and the maximum current which could be developed was limited as 2A, the effect of dewatering at higher current could not be investigated. It is suggested that experiments should

be conducted to investigate the effect of dewatering at higher current, using a higher voltage output power supply. The experimental results would provide a good comparison to the results obtained in this research.

3. In this research, the experiments were conducted at laboratory scale where the positive effect of electroosmotic dewatering under constant current was reported. It is recommended that a full-scale belt filter press combined with electroosmotic dewatering under constant current should be developed.

4. The main problem of using copper as electrodes is corrosion due to electrochemical reactions. Moreover, copper is too hard to be used in a belt press machine. The concept of electrokinetic geosynthetics (EKGs) should be applied to develop electrodes as a conductive carbon filter cloth, which is suitable to be used in a full-scale belt press system and has the capability of overcoming corrosion.

5. An increasing body of evidence suggests that reversal of electrode polarity or current direction during electroosmosis can increase the efficiency of the dewatering process. In this research, however, polarity reversal was not considered in the design framework. It is recommended that investigation of the effect of polarity reversal should be carried out and the best time to reverse electrode polarity should be analysed and predicted for the purpose of design.

6. In this research, one-dimensional electroosmotic flow between two parallel electrodes was considered. However, in some cases (e.g. an in-situ electroosmotic dewatering system using 'wick' drains), two-dimensional electroosmotic flow occurs subject to a non-linear electric field. Therefore, the research should be extended to solve the problem of two-dimensional electroosmotic flow. Because the flow is related to complex mathematical formulations and boundary conditions, it is suggested to solve it by using numerical methods.

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APPENDIX

Data of Experimental Testings

Electroosmotic Dewatering Test of Humic Sludge (3 Days)

Start Date	26/2/2003		Length	13	cm
Start Time	9:00		Solid Content	16	%
Voltage	13	V	Pressure	50	kPa
Area of Cell	0.0161	m^2	Mass of Sample	2234	g

			EK + Pressure				
Date	*Time*	*Time (min)*	*Current (A)*	*Volume Out (ml)*	*Resistance (Ohm)*	*Solid Content (%)*	*Power Consumption (Wh)*
26/2/2003	9:00	0	0.321	0	40.50	16.0	0
26/2/2003	9:05	5	0.316	0	41.14	16.0	0.345
26/2/2003	9:10	10	0.313	0	41.53	16.0	0.686
26/2/2003	9:15	15	0.310	0	41.94	16.0	1.023
26/2/2003	9:20	20	0.306	0	42.48	16.0	1.357
26/2/2003	9:25	25	0.301	0	43.19	16.0	1.686
26/2/2003	9:30	30	0.297	2	43.77	16.0	2.010
26/2/2003	9:35	35	0.293	6	44.37	16.0	2.329
26/2/2003	9:40	40	0.289	10	44.98	16.1	2.644
26/2/2003	9:45	45	0.285	13	45.61	16.1	2.955
26/2/2003	10:00	60	0.273	19	47.62	16.1	3.862
26/2/2003	10:15	75	0.263	25	49.43	16.2	4.733
26/2/2003	10:30	90	0.252	31	51.59	16.2	5.570
26/2/2003	10:45	105	0.243	38	53.50	16.3	6.374
26/2/2003	11:00	120	0.234	43	55.56	16.3	7.149
26/2/2003	11:15	135	0.229	46	56.77	16.3	7.902
26/2/2003	11:30	150	0.223	51	58.30	16.4	8.636
26/2/2003	12:00	180	0.212	62	61.32	16.5	10.050
26/2/2003	12:30	210	0.203	69	64.04	16.5	11.399
26/2/2003	13:00	240	0.195	79	66.67	16.6	12.692
26/2/2003	13:30	270	0.209	93	62.20	16.7	14.005
26/2/2003	14:00	300	0.200	105	65.00	16.8	15.335
26/2/2003	14:30	330	0.195	113	66.67	16.9	16.618
26/2/2003	15:30	390	0.183	130	71.04	17.0	19.075
26/2/2003	16:30	450	0.182	155	71.43	17.2	21.448
26/2/2003	17:30	510	0.174	174	74.71	17.4	23.762
26/2/2003	18:30	570	0.166	187	78.31	17.5	25.972
26/2/2003	19:30	630	0.158	203	82.28	17.6	28.078

26/2/2003	21:30	750	0.141	250	92.20	18.0	31.965
26/2/2003	23:30	870	0.125	303	104.00	18.5	35.423
27/2/2003	1:30	990	0.111	376	117.12	19.2	38.491
27/2/2003	3:30	1110	0.099	421	131.31	19.7	41.221
27/2/2003	6:30	1290	0.091	493	142.86	20.5	44.926
27/2/2003	7:30	1350	0.088	511	147.73	20.7	46.089
27/2/2003	8:30	1410	0.084	530	154.76	21.0	47.207
27/2/2003	9:30	1470	0.080	549	162.50	21.2	48.273
27/2/2003	10:00	1500	0.079	558	164.56	21.3	48.790
27/2/2003	11:00	1560	0.077	572	168.83	21.5	49.804
27/2/2003	12:00	1620	0.078	587	166.67	21.7	50.812
27/2/2003	13:00	1680	0.076	599	171.05	21.9	51.813
27/2/2003	14:00	1740	0.076	613	171.05	22.1	52.801
27/2/2003	15:00	1800	0.074	627	175.68	22.2	53.776
27/2/2003	16:00	1860	0.074	638	175.68	22.4	54.738
27/2/2003	18:00	1980	0.072	658	180.56	22.7	56.636
27/2/2003	19:00	2040	0.071	668	183.10	22.8	57.565
27/2/2003	21:00	2160	0.067	691	194.03	23.2	59.359
27/2/2003	23:00	2280	0.063	729	206.35	23.8	61.049
28/2/2003	1:00	2400	0.059	764	220.34	24.3	62.635
28/2/2003	3:00	2520	0.057	791	228.07	24.8	64.143
28/2/2003	5:00	2640	0.056	816	232.14	25.2	65.612
28/2/2003	7:00	2760	0.051	838	254.90	25.6	67.003
28/2/2003	9:00	2880	0.046	855	282.61	25.9	68.264
28/2/2003	13:00	3120	0.040	876	325.00	26.3	70.500
28/2/2003	14:00	3180	0.039	880	333.33	26.4	71.014
28/2/2003	15:00	3240	0.038	884	342.11	26.5	71.514
28/2/2003	16:00	3300	0.037	886	351.35	26.5	72.002
28/2/2003	17:00	3360	0.036	888	361.11	26.6	72.476
28/2/2003	18:00	3420	0.035	890	371.43	26.6	72.938
28/2/2003	19:00	3480	0.033	892	393.94	26.6	73.380
28/2/2003	22:00	3660	0.030	895	433.33	26.7	74.608
28/2/2003	23:00	3720	0.029	896	448.28	26.7	74.992
1/3/2003	9:00	4320	0.020	897	650.00	26.7	78.177

Electroosmotic Dewatering Test of Humic Sludge with Sawduct (3 Days)

Start Date	3/3/2003		Length	13	cm
Start Time	17:00		Solid Content	24	%
Voltage	13	V	Pressure	50	kPa
Area of Cell	0.0161	m^2	Mass of Sample	2234	g

			EK + Pressure				
Date	*Time*	*Time (min)*	*Current (A)*	*Volume Out (ml)*	*Resistance (Ohm)*	*Solid Content (%)*	*Power Consumption (Wh)*
3/3/2003	17:00	0	0.277	0	46.93	24.0	0
3/3/2003	17:05	5	0.27	0	48.15	24.0	0.296
3/3/2003	17:10	10	0.267	0	48.69	24.0	0.587
3/3/2003	17:15	15	0.264	0	49.24	24.0	0.875
3/3/2003	17:20	20	0.261	0	49.81	24.0	1.159
3/3/2003	17:25	25	0.258	0	50.39	24.0	1.440
3/3/2003	17:30	30	0.256	0	50.78	24.0	1.719
3/3/2003	17:35	35	0.253	3	51.38	24.0	1.994
3/3/2003	17:40	40	0.25	8	52.00	24.1	2.267
3/3/2003	17:45	45	0.248	11	52.42	24.1	2.537
3/3/2003	18:00	60	0.251	26	51.79	24.3	3.348
3/3/2003	18:15	75	0.245	37	53.06	24.4	4.154
3/3/2003	18:30	90	0.238	47	54.62	24.5	4.938
3/3/2003	18:45	105	0.231	54	56.28	24.6	5.701
3/3/2003	19:00	120	0.226	61	57.52	24.7	6.443
3/3/2003	19:15	135	0.22	69	59.09	24.8	7.168
3/3/2003	19:30	150	0.215	78	60.47	24.9	7.875
3/3/2003	20:00	180	0.207	90	62.80	25.0	9.246
3/3/2003	20:30	210	0.197	107	65.99	25.2	10.559
3/3/2003	21:00	240	0.189	113	68.78	25.3	11.814
3/3/2003	21:30	270	0.18	129	72.22	25.5	13.013
3/3/2003	22:00	300	0.171	142	76.02	25.6	14.154
3/3/2003	23:00	360	0.154	166	84.42	25.9	16.266
4/3/2003	1:00	480	0.128	210	101.56	26.5	19.932
4/3/2003	3:00	600	0.105	248	123.81	27.0	22.961
4/3/2003	6:00	780	0.09	292	144.44	27.6	26.764
4/3/2003	14:00	1260	0.066	393	196.97	29.1	34.876
4/3/2003	15:00	1320	0.064	403	203.13	29.3	35.721

4/3/2003	17:00	1440	0.061	423	213.11	29.6	37.346
4/3/2003	22:00	1740	0.052	465	250.00	30.3	41.018
5/3/2003	0:00	1860	0.05	479	260.00	30.6	42.344
5/3/2003	2:00	1980	0.048	495	270.83	30.8	43.618
5/3/2003	12:00	2580	0.04	561	325.00	32.0	49.338
5/3/2003	14:00	2700	0.039	572	333.33	32.3	50.365
5/3/2003	16:00	2820	0.039	583	333.33	32.5	51.379
5/3/2003	18:00	2940	0.038	595	342.11	32.7	52.380
5/3/2003	20:00	3060	0.036	603	361.11	32.9	53.342
5/3/2003	22:00	3180	0.035	612	371.43	33.1	54.265
6/3/2003	0:00	3300	0.034	620	382.35	33.2	55.162
6/3/2003	2:00	3420	0.033	627	393.94	33.4	56.033
6/3/2003	4:00	3540	0.032	633	406.25	33.5	56.878
6/3/2003	8:00	3780	0.031	647	419.35	33.8	58.516
6/3/2003	10:00	3900	0.031	652	419.35	33.9	59.322
6/3/2003	12:00	4020	0.03	657	433.33	34.0	60.115
6/3/2003	14:00	4140	0.029	662	448.28	34.1	60.882
6/3/2003	16:00	4260	0.028	667	464.29	34.2	61.623
6/3/2003	17:00	4320	0.028	670	464.29	34.3	61.987

Electroosmotic Dewatering Test of Sewage Sludge A from Rock Farm Lagoon (3 Days)

Start Date	11/3/2003		Length	13	cm
Start Time	0:30		Solid Content	15.7	%
Voltage	13	V	Pressure	50	kPa
Area of Cell	0.0161	m^2	Mass of Sampl	2234	g

			EK + Pressure				
Date	*Time*	*Time (min)*	*Current (A)*	*Volume Out (ml)*	*Resistance (Ohm)*	*Solid Content (%)*	*Power Consumption (Wh)*
11/3/2003	0:30	0	0.554	0	23.47	15.7	0
11/3/2003	0:35	5	0.503	0	25.84	15.7	0.573
11/3/2003	0:40	10	0.441	0	29.48	15.7	1.084
11/3/2003	0:45	15	0.403	0	32.26	15.7	1.541
11/3/2003	0:50	20	0.414	0	31.40	15.7	1.984
11/3/2003	0:55	25	0.405	0	32.10	15.7	2.427
11/3/2003	1:00	30	0.394	0	32.99	15.7	2.860
11/3/2003	1:15	45	0.360	0	36.11	15.7	4.085
11/3/2003	1:30	60	0.325	0	40.00	15.7	5.198
11/3/2003	1:45	75	0.295	0	44.07	15.7	6.206
11/3/2003	2:00	90	0.270	7	48.15	15.7	7.124
11/3/2003	2:30	120	0.226	17	57.52	15.8	8.736
11/3/2003	3:00	150	0.188	23	69.15	15.9	10.082
11/3/2003	4:00	210	0.144	36	90.28	16.0	12.240
11/3/2003	5:00	270	0.134	47	97.01	16.0	14.047
11/3/2003	6:00	330	0.112	56	116.07	16.1	15.646
11/3/2003	7:00	390	0.100	62	130.00	16.1	17.024
11/3/2003	8:00	450	0.092	70	141.30	16.2	18.272
11/3/2003	9:00	510	0.085	78	152.94	16.3	19.422
11/3/2003	11:00	630	0.073	92	178.08	16.4	21.476
11/3/2003	13:00	750	0.064	101	203.13	16.4	23.257
11/3/2003	15:00	870	0.053	112	245.28	16.5	24.778
11/3/2003	17:00	990	0.043	120	302.33	16.6	26.026
11/3/2003	19:00	1110	0.036	130	361.11	16.7	27.053
11/3/2003	21:00	1230	0.031	136	419.35	16.7	27.924
12/3/2003	0:30	1440	0.025	148	520.00	16.8	29.198
12/3/2003	6:30	1800	0.020	162	650.00	16.9	30.953
12/3/2003	12:30	2160	0.016	173	812.50	17.0	32.357

12/3/2003	15:30	2340	0.016	176	812.50	17.0	32.981
12/3/2003	18:30	2520	0.016	181	812.50	17.1	33.605
13/3/2003	0:30	2880	0.014	190	928.57	17.2	34.775
13/3/2003	2:30	3000	0.014	193	928.57	17.2	35.139
13/3/2003	12:30	3600	0.014	205	928.57	17.3	36.959
13/3/2003	15:30	3780	0.014	208	928.57	17.3	37.505
13/3/2003	18:30	3960	0.013	211	1000.00	17.3	38.032
13/3/2003	21:30	4140	0.013	214	1000.00	17.4	38.539
14/3/2003	0:30	4320	0.013	216	1000.00	17.4	39.046

Electroosmotic Dewatering Test of Sewage Sludge B from Minnworth Lagoon (3 Days)

Start Date	16/3/2003		Length	13	cm
Start Time	21:00		Solid Content	9.1	%
Voltage	13	V	Pressure	50	kPa
Area of Cell	0.0161	m^2	Mass of Sample	2234	g

			EK + Pressure				
Date	*Time*	*Time (min)*	*Current (A)*	*Volume Out (ml)*	*Resistance (Ohm)*	*Solid Content (%)*	*Power Consumption (Wh)*
16/3/2003	21:00	0	0.285	0	45.61	9.1	0
16/3/2003	21:05	5	0.278	0	46.76	9.1	0.305
16/3/2003	21:10	10	0.274	0	47.45	9.1	0.604
16/3/2003	21:15	15	0.269	0	48.33	9.1	0.898
16/3/2003	21:20	20	0.262	0	49.62	9.1	1.186
16/3/2003	21:25	25	0.254	0	51.18	9.1	1.465
16/3/2003	21:30	30	0.247	0	52.63	9.1	1.737
16/3/2003	21:45	45	0.219	0	59.36	9.1	2.494
16/3/2003	22:00	60	0.179	0	72.63	9.1	3.141
16/3/2003	22:15	75	0.132	6	98.48	9.1	3.646
16/3/2003	22:30	90	0.170	16	76.47	9.2	4.137
16/3/2003	23:00	120	0.104	26	125.00	9.2	5.027
16/3/2003	23:30	150	0.075	33	173.33	9.2	5.609
17/3/2003	0:00	180	0.060	37	216.67	9.3	6.048
17/3/2003	1:00	240	0.044	45	295.45	9.3	6.724
17/3/2003	2:00	300	0.057	55	228.07	9.3	7.380
17/3/2003	3:00	360	0.045	61	288.89	9.4	8.043
17/3/2003	4:00	420	0.038	66	342.11	9.4	8.583
17/3/2003	5:00	480	0.033	70	393.94	9.4	9.044
17/3/2003	7:00	600	0.028	79	464.29	9.4	9.837
17/3/2003	9:00	720	0.022	88	590.91	9.5	10.487
17/3/2003	11:00	840	0.018	97	722.22	9.5	11.007
17/3/2003	13:00	960	0.015	102	866.67	9.5	11.436
17/3/2003	15:00	1080	0.014	104	928.57	9.5	11.813
17/3/2003	17:00	1200	0.013	105	1000.00	9.5	12.164
17/3/2003	19:00	1320	0.012	109	1083.33	9.6	12.489
17/3/2003	22:00	1500	0.011	112	1181.82	9.6	12.938
18/3/2003	12:00	2340	0.008	125	1625.00	9.6	14.667

18/3/2003	13:00	2400	0.008	125	1625.00	9.6	14.771
18/3/2003	15:00	2520	0.008	128	1625.00	9.7	14.979
18/3/2003	17:00	2640	0.008	130	1625.00	9.7	15.187
18/3/2003	20:00	2820	0.008	132	1625.00	9.7	15.499
19/3/2003	0:00	3060	0.008	136	1625.00	9.7	15.915
19/3/2003	3:00	3240	0.008	138	1625.00	9.7	16.227
19/3/2003	6:00	3420	0.007	141	1857.14	9.7	16.519
19/3/2003	9:00	3600	0.007	141	1857.14	9.7	16.792
19/3/2003	12:00	3780	0.007	144	1857.14	9.7	17.065
19/3/2003	17:00	4080	0.007	149	1857.14	9.8	17.520
19/3/2003	21:00	4320	0.007	153	1857.14	9.8	17.884

Electroosmotic Dewatering Test of Humic Sludge (3 Days)

Start Date	26/2/2003		Length	13	cm
Start Time	9:00		Solid Content	16	%
Voltage	0	V	Pressure	50	kPa
Area of Cell	0.0161	m^2	Mass of Sample	2234	g

			Control	
Date	*Time*	*Time (min)*	*Volume Out (ml)*	*Solid Content (%)*
26/2/2003	9:00	0	0	16.0
26/2/2003	9:05	5	0	16.0
26/2/2003	9:10	10	0	16.0
26/2/2003	9:15	15	0	16.0
26/2/2003	9:20	20	0	16.0
26/2/2003	9:25	25	0	16.0
26/2/2003	9:30	30	0	16.0
26/2/2003	9:35	35	0	16.0
26/2/2003	9:40	40	0	16.0
26/2/2003	9:45	45	0	16.0
26/2/2003	10:00	60	3	16.0
26/2/2003	10:15	75	6	16.0
26/2/2003	10:30	90	9	16.1
26/2/2003	10:45	105	17	16.1
26/2/2003	11:00	120	18	16.1
26/2/2003	11:15	135	19	16.1
26/2/2003	11:30	150	28	16.2
26/2/2003	12:00	180	32	16.2
26/2/2003	12:30	210	38	16.3
26/2/2003	13:00	240	44	16.3
26/2/2003	13:30	270	49	16.4
26/2/2003	14:00	300	55	16.4
26/2/2003	14:30	330	58	16.4
26/2/2003	15:30	390	66	16.5
26/2/2003	16:30	450	75	16.6
26/2/2003	17:30	510	81	16.6
26/2/2003	18:30	570	88	16.7
26/2/2003	19:30	630	91	16.7

26/2/2003	21:30	750	101	16.8
26/2/2003	23:30	870	110	16.8
27/2/2003	1:30	990	119	16.9
27/2/2003	3:30	1110	125	16.9
27/2/2003	6:30	1290	135	17.0
27/2/2003	7:30	1350	139	17.1
27/2/2003	8:30	1410	141	17.1
27/2/2003	9:30	1470	144	17.1
27/2/2003	10:00	1500	145	17.1
27/2/2003	11:00	1560	149	17.1
27/2/2003	12:00	1620	153	17.2
27/2/2003	13:00	1680	155	17.2
27/2/2003	14:00	1740	157	17.2
27/2/2003	15:00	1800	161	17.2
27/2/2003	16:00	1860	162	17.3
27/2/2003	18:00	1980	169	17.3
27/2/2003	19:00	2040	172	17.3
27/2/2003	21:00	2160	179	17.4
27/2/2003	23:00	2280	187	17.5
28/2/2003	1:00	2400	192	17.5
28/2/2003	3:00	2520	197	17.5
28/2/2003	5:00	2640	200	17.6
28/2/2003	7:00	2760	204	17.6
28/2/2003	9:00	2880	208	17.6
28/2/2003	13:00	3120	213	17.7
28/2/2003	14:00	3180	215	17.7
28/2/2003	15:00	3240	217	17.7
28/2/2003	16:00	3300	218	17.7
28/2/2003	17:00	3360	219	17.7
28/2/2003	18:00	3420	220	17.7
28/2/2003	19:00	3480	222	17.8
28/2/2003	22:00	3660	226	17.8
28/2/2003	23:00	3720	227	17.8
1/3/2003	9:00	4320	237	17.9

Electroosmotic Dewatering Test of Humic Sludge with Sawduct (3 Days)

Start Date	3/3/2003		Length	13	cm
Start Time	17:00		Solid Content	24	%
Voltage	0	V	Pressure	50	kPa
Area of Cell	0.0161	m^2	Mass of Sample	2234	g

			Control	
Date	*Time*	*Time (min)*	*Volume Out (ml)*	*Solid Content (%)*
3/3/2003	17:00	0	0	24.0
3/3/2003	17:05	5	0	24.0
3/3/2003	17:10	10	0	24.0
3/3/2003	17:15	15	0	24.0
3/3/2003	17:20	20	0	24.0
3/3/2003	17:25	25	0	24.0
3/3/2003	17:30	30	0	24.0
3/3/2003	17:35	35	0	24.0
3/3/2003	17:40	40	0	24.0
3/3/2003	17:45	45	0	24.0
3/3/2003	18:00	60	0	24.0
3/3/2003	18:15	75	0	24.0
3/3/2003	18:30	90	0	24.0
3/3/2003	18:45	105	3	24.0
3/3/2003	19:00	120	7	24.1
3/3/2003	19:15	135	8	24.1
3/3/2003	19:30	150	10	24.1
3/3/2003	20:00	180	11	24.1
3/3/2003	20:30	210	13	24.1
3/3/2003	21:00	240	14	24.2
3/3/2003	21:30	270	15	24.2
3/3/2003	22:00	300	16	24.2
3/3/2003	23:00	360	18	24.2
4/3/2003	1:00	480	21	24.2
4/3/2003	3:00	600	24	24.3
4/3/2003	6:00	780	29	24.3
4/3/2003	14:00	1260	44	24.5
4/3/2003	15:00	1320	45	24.5

4/3/2003	17:00	1440	48	24.5
4/3/2003	22:00	1740	54	24.6
5/3/2003	0:00	1860	57	24.6
5/3/2003	2:00	1980	58	24.6
5/3/2003	12:00	2580	64	24.7
5/3/2003	14:00	2700	65	24.7
5/3/2003	16:00	2820	65	24.7
5/3/2003	18:00	2940	67	24.7
5/3/2003	20:00	3060	68	24.8
5/3/2003	22:00	3180	68	24.8
6/3/2003	0:00	3300	68	24.8
6/3/2003	2:00	3420	70	24.8
6/3/2003	4:00	3540	71	24.8
6/3/2003	8:00	3780	71	24.8
6/3/2003	10:00	3900	71	24.8
6/3/2003	12:00	4020	72	24.8
6/3/2003	14:00	4140	72	24.8
6/3/2003	16:00	4260	73	24.8
6/3/2003	17:00	4320	73	24.8

Electroosmotic Dewatering Test of Sewage Sludge A from Rock Farm Lagoon (3 Days)

Start Date	25/2/2003		Length	13	cm
Start Time	9:00		Solid Content	15.7	%
Voltage	0	V	Pressure	50	kPa
Area of Cell	0.0161	m^2	Mass of Sample	2234	g

			CONTROL	
Date	*Time*	*Time (min)*	*Volume Out (ml)*	*Solid Content (%)*
25/2/2003	9:00	0	0	15.7
25/2/2003	9:05	5	0	15.7
25/2/2003	9:10	10	0	15.7
25/2/2003	9:15	15	0	15.7
25/2/2003	9:20	20	0	15.7
25/2/2003	9:25	25	0	15.7
25/2/2003	9:30	30	0	15.7
25/2/2003	9:45	45	0	15.7
25/2/2003	10:00	60	0	15.7
25/2/2003	10:15	75	0	15.7
25/2/2003	10:30	90	0	15.7
25/2/2003	10:45	105	0	15.7
25/2/2003	11:00	120	0	15.7
25/2/2003	11:30	150	0	15.7
25/2/2003	12:00	180	0	15.7
25/2/2003	12:30	210	0	15.7
25/2/2003	13:00	240	0	15.7
25/2/2003	13:30	270	0	15.7
25/2/2003	14:00	300	0	15.7
25/2/2003	15:00	360	0	15.7
25/2/2003	16:00	420	0	15.7
25/2/2003	18:00	540	0	15.7
25/2/2003	19:00	600	0	15.7
25/2/2003	21:00	720	0	15.7
25/2/2003	23:00	840	0	15.7
26/2/2003	1:00	960	0	15.7
26/2/2003	3:00	1080	0	15.7
26/2/2003	5:00	1200	0	15.7

26/2/2003	7:00	1320	0	15.7
26/2/2003	9:00	1440	0	15.7
26/2/2003	13:00	1680	0	15.7
26/2/2003	14:00	1740	0	15.7
26/2/2003	15:00	1800	0	15.7
26/2/2003	16:00	1860	0	15.7
26/2/2003	17:00	1920	0	15.7
26/2/2003	18:00	1980	0	15.7
26/2/2003	19:00	2040	0	15.7
26/2/2003	22:00	2220	6	15.7
26/2/2003	23:00	2280	7	15.7
27/2/2003	9:00	2880	9	15.8
27/2/2003	10:00	2940	9	15.8
27/2/2003	11:00	3000	9	15.8
27/2/2003	12:00	3060	9	15.8
27/2/2003	14:00	3180	10	15.8
27/2/2003	16:00	3300	10	15.8
27/2/2003	18:00	3420	10	15.8
27/2/2003	20:00	3540	10	15.8
27/2/2003	22:00	3660	10	15.8
28/2/2003	0:00	3780	10	15.8
28/2/2003	2:00	3900	11	15.8
28/2/2003	4:00	4020	11	15.8
28/2/2003	6:00	4140	11	15.8
28/2/2003	9:00	4320	13	15.8

Electroosmotic Dewatering Test of Sewage Sludge B from Minnworth Lagoon (3 Days)

Start Date	16/3/2003		Length	13	cm
Start Time	21:00		SD	9.1	%
Voltage	13	V	Pressure	50	kPa
Area of Cell	0.0161	m^2	Mass of Sample	2234	g

			Control	
Date	*Time*	*Time (min)*	*Volume Out (ml)*	*Solid Content (%)*
16/3/2003	21:00	0	0	9.1
16/3/2003	21:05	5	0	9.1
16/3/2003	21:10	10	0	9.1
16/3/2003	21:15	15	0	9.1
16/3/2003	21:20	20	0	9.1
16/3/2003	21:25	25	0	9.1
16/3/2003	21:30	30	0	9.1
16/3/2003	21:45	45	0	9.1
16/3/2003	22:00	60	0	9.1
16/3/2003	22:15	75	0	9.1
16/3/2003	22:30	90	0	9.1
16/3/2003	23:00	120	0	9.1
16/3/2003	23:30	150	0	9.1
17/3/2003	0:00	180	0	9.1
17/3/2003	1:00	240	0	9.1
17/3/2003	2:00	300	0	9.1
17/3/2003	3:00	360	0	9.1
17/3/2003	4:00	420	0	9.1
17/3/2003	5:00	480	0	9.1
17/3/2003	7:00	600	0	9.1
17/3/2003	9:00	720	0	9.1
17/3/2003	11:00	840	0	9.1
17/3/2003	13:00	960	0	9.1
17/3/2003	15:00	1080	0	9.1
17/3/2003	17:00	1200	3	9.1
17/3/2003	19:00	1320	7	9.1
17/3/2003	22:00	1500	10	9.1
18/3/2003	12:00	2340	22	9.2

18/3/2003	13:00	2400	23	9.2
18/3/2003	15:00	2520	26	9.2
18/3/2003	17:00	2640	27	9.2
18/3/2003	20:00	2820	29	9.2
19/3/2003	0:00	3060	32	9.2
19/3/2003	3:00	3240	34	9.2
19/3/2003	6:00	3420	36	9.2
19/3/2003	9:00	3600	38	9.3
19/3/2003	12:00	3780	40	9.3
19/3/2003	17:00	4080	44	9.3
19/3/2003	21:00	4320	46	9.3

Electroosmotic Dewatering Test of Humic Sludge (Copper, Constant Voltage, 25kPa, 500g)

EK Dewatering with Constant Voltage

Date	15/10/2003		**Initial Solid Concentration**	16.4	%
Pressure	25	kPa	**Mass of Sample**	500	g

		15V					
Time (min)	Log Time	Voltage (V)	Current (A)	Resistance (Ohm)	Volume (ml)	Solid Concentration (%)	Power Consumption (Wh)
1	0.00	13.40	2.000	6.70	0.0	16.4	0.447
2	0.69	13.88	2.000	6.94	0.0	16.4	0.901
3	1.10	14.30	2.000	7.15	0.0	16.4	1.371
4	1.39	14.69	2.000	7.35	2.0	16.5	1.854
5	1.61	15.00	2.000	7.50	5.0	16.6	2.349
6	1.79	15.00	1.988	7.55	7.0	16.6	2.848
7	1.95	15.00	1.927	7.78	9.0	16.7	3.337
8	2.08	15.00	1.877	7.99	14.0	16.9	3.812
9	2.20	15.00	1.823	8.23	18.0	17.0	4.275
10	2.30	15.00	1.780	8.43	20.0	17.1	4.725
11	2.40	15.00	1.740	8.62	23.0	17.2	5.165
12	2.48	15.00	1.700	8.82	26.0	17.3	5.595
13	2.56	15.00	1.662	9.03	29.0	17.4	6.016
14	2.64	15.00	1.622	9.25	31.0	17.5	6.426
15	2.71	15.00	1.588	9.45	33.0	17.6	6.827
16	2.77	15.00	1.551	9.67	36.0	17.7	7.220
17	2.83	15.00	1.521	9.86	39.0	17.8	7.604
18	2.89	15.00	1.491	10.06	41.5	17.9	7.980
19	2.94	15.00	1.458	10.29	44.0	18.0	8.349
20	3.00	15.00	1.433	10.47	46.5	18.1	8.710
21	3.04	15.00	1.404	10.68	49.0	18.2	9.065
22	3.09	15.00	1.381	10.86	51.0	18.3	9.413
23	3.14	15.00	1.355	11.07	53.0	18.3	9.755
24	3.18	15.00	1.338	11.21	55.0	18.4	10.092
25	3.22	15.00	1.320	11.36	56.5	18.5	10.424
26	3.26	15.00	1.296	11.57	58.0	18.6	10.751
27	3.30	15.00	1.273	11.78	59.0	18.6	11.072
28	3.33	15.00	1.251	11.99	60.5	18.7	11.387
29	3.37	15.00	1.230	12.20	63.0	18.8	11.698
30	3.40	15.00	1.209	12.41	64.5	18.8	12.002
35	3.56	15.00	1.082	13.86	71.0	19.1	13.434
40	3.69	15.00	0.961	15.61	76.5	19.4	14.711
45	3.81	15.00	0.863	17.38	81.0	19.6	15.851
50	3.91	15.00	0.771	19.46	85.0	19.8	16.872
55	4.01	15.00	0 669	22.42	88.5	19.9	17.772
60	4 09	15.00	0.553	27.12	91.5	20.1	18.536

Electroosmotic Dewatering Test of Humic Sludge (Copper, Constant Voltage, 25kPa, 500g)

EK Dewatering with Constant Voltage

Date	23/10/2003		**Initial Solid Concentration**	15.3	%
Pressure	25	kPa	**Mass of Sample**	500	g

		10V					
Time (min)	Log Time	Voltage (V)	Current (A)	Resistance (Ohm)	Volume (ml)	Solid Concentration (%)	Power Consumption (Wh)
1	0.00	10.00	1.340	7.46	0.0	15.3	0.223
2	0.69	10.00	1.303	7.67	0.0	15.3	0.444
3	1.10	10.00	1.267	7.89	0.0	15.3	0.658
4	1.39	10.00	1.236	8.09	0.0	15.3	0.866
5	1.61	10.00	1.214	8.24	0.0	15.3	1.071
6	1.79	10.00	1.191	8.40	0.0	15.3	1.271
7	1.95	10.00	1.173	8.53	0.5	15.3	1.468
8	2.08	10.00	1.153	8.67	1.5	15.3	1.662
9	2.20	10.00	1.137	8.80	2.5	15.4	1.853
10	2.30	10.00	1.118	8.94	4.0	15.4	2.041
11	2.40	10.00	1.098	9.11	6.0	15.5	2.225
12	2.48	10.00	1.079	9.27	7.5	15.5	2.407
13	2.56	10.00	1.060	9.43	9.0	15.6	2.585
14	2 64	10.00	1.041	9.61	10.0	15.6	2.760
15	2.71	10.00	1.023	9.78	12.0	15.7	2.932
16	2.77	10.00	1.005	9.95	14.0	15.7	3.101
17	2.83	10.00	0.989	10.11	16.0	15.8	3.267
18	2.89	10.00	0.973	10.28	17.5	15.9	3.431
19	2.94	10.00	0.957	10.45	19.0	15.9	3.591
20	3.00	10.00	0.942	10.62	21.0	16.0	3.750
21	3.04	10.00	0.928	10.78	22.5	16.0	3.906
22	3.09	10.00	0.915	10.93	24.5	16.1	4.059
23	3.14	10.00	0.901	11.10	26.0	16.1	4.210
24	3.18	10.00	0.888	11.26	27.5	16.2	4.360
25	3.22	10.00	0.877	11.40	29.0	16.2	4.507
26	3.26	10.00	0.866	11.55	30.5	16.3	4.652
27	3.30	10.00	0.855	11.70	32.0	16.3	4.795
28	3.33	10.00	0.844	11.85	33.5	16.4	4.937
29	3.37	10.00	0.834	11.99	34.5	16.4	5.077
30	3.40	10.00	0.822	12.17	35.5	16.5	5.215
35	3.56	10.00	0.772	12.95	42.0	16.7	5.879
40	3.69	10.00	0.727	13.76	48.0	16.9	6.503
45	3.81	10.00	0.689	14.51	53.0	17.1	7.093
50	3.91	10.00	0.648	15.43	58.0	17.3	7.651
55	4.01	10.00	0.611	16.37	61.5	17.4	8.175
60	4.09	10.00	0.576	17.36	65.0	17.6	8.670

EK Dewatering Test of Humic Sludge (Copper, Constant Current, 25kPa, 500g)

EK Dewatering with Constant Current

Date	19/10/2003		**Initial Solid Concentration**	16.5	%
Pressure	25	kPa	**Mass of Sample**	500	g

		1.0A					
Time (min)	Log Time	Voltage (V)	Current (A)	Resistance (Ohm)	Volume (ml)	Solid Concentration (%)	Power Consumption (Wh)
1	0.00	8.22	1.0	8.22	0.0	16.5	0.137
2	0.69	8.41	1.0	8.41	0.0	16.5	0.276
3	1.10	8.59	1.0	8.59	0.0	16.5	0.417
4	1.39	8.77	1.0	8.77	0.0	16.5	0.562
5	1.61	8.94	1.0	8.94	0.0	16.5	0.710
6	1.79	9.08	1.0	9.08	0.0	16.5	0.860
7	1.95	9.24	1.0	9.24	0.0	16.5	1.012
8	2.08	9.39	1.0	9.39	0.0	16.5	1.168
9	2.20	9.56	1.0	9.56	0.0	16.5	1.326
10	2.30	9.72	1.0	9.72	0.0	16.5	1.486
11	2.40	9.91	1.0	9.91	1.0	16.5	1.650
12	2.48	10.09	1.0	10.09	2.0	16.6	1.816
13	2.56	10.28	1.0	10.28	4.0	16.6	1.986
14	2.64	10.48	1.0	10.48	6.0	16.7	2.159
15	2.71	10.70	1.0	10.70	8.0	16.8	2.336
16	2.77	10.91	1.0	10.91	10.0	16.8	2.516
17	2.83	11.11	1.0	11.11	12.0	16.9	2.699
18	2.89	11.24	1.0	11.24	14.0	17.0	2.886
19	2.94	11.40	1.0	11.40	16 0	17.0	3.074
20	3.00	11.58	1.0	11.58	18.0	17.1	3.266
21	3.04	11.80	1.0	11.80	20.0	17.2	3.461
22	3.09	12.02	1.0	12.02	22.0	17.3	3.659
23	3.14	12.25	1.0	12.25	24.0	17.3	3.861
24	3.18	12.47	1.0	12.47	26.0	17.4	4.067
25	3.22	12.67	1.0	12.67	28.0	17.5	4.277
26	3.26	12.90	1.0	12.90	30.0	17.6	4.490
27	3.30	13.11	1.0	13.11	32.0	17.6	4.707
28	3.33	13.33	1.0	13.33	34.0	17.7	4.927
29	3.37	13.56	1.0	13.56	36.0	17.8	5.151
30	3.40	13.79	1.0	13.79	38.0	17.9	5.379
35	3.56	14.99	1.0	14.99	48.5	18.3	6.578
40	3.69	16.32	1.0	16.32	58.0	18.7	7.883
45	3.81	18.47	1.0	18.47	65.0	19.0	9.332
50	3.91	22.30	1.0	22.30	72.0	19.3	11.031
55	4.01	30.00	0.992	30.24	78.5	19.6	13.201
60	4.09	30.00	0.730	41.10	83.0	19.8	15.354

EK Dewatering Test of Humic Sludge (Copper, Constant Current, 25kPa, 500g)

EK Dewatering with Constant Current

Date	10/10/2003		**Initial Solid Concentration**	16.4	%
Pressure	25	kPa	**Mass of Sample**	500	g

		2.0A					
Time (min)	Log Time	Voltage (V)	Current (A)	Resistance (Ohm)	Volume (ml)	Solid Concentration (%)	Power Consumption (Wh)
1	0.00	15.60	2.00	7.80	0.0	16.4	0.520
2	0.69	16.16	2.00	8.08	0.0	16.4	1.049
3	1.10	16.64	2.00	8.32	0.0	16.4	1.596
4	1.39	17.20	2.00	8.60	0.0	16.4	2.160
5	1.61	17.75	2.00	8.88	0.0	16.4	2.743
6	1.79	18.41	2.00	9.21	2.0	16.5	3.345
7	1.95	19.06	2.00	9.53	7.0	16.6	3.970
8	2.08	19.70	2.00	9.85	12.0	16.8	4.616
9	2.20	20.50	2.00	10.25	16.0	16.9	5.286
10	2.30	21.20	2.00	10.60	20.0	17.1	5.981
11	2.40	21.90	2.00	10.95	24.0	17.2	6.699
12	2.48	22.60	2.00	11.30	28.0	17.4	7.441
13	2.56	23.30	2.00	11.65	32.0	17.5	8.206
14	2.64	23.60	2.00	11.80	36.0	17.7	8.987
15	2.71	24.80	2.00	12.40	40.0	17.8	9.794
16	2.77	25.50	2.00	12.75	43.0	17.9	10.632
17	2.83	26.50	2.00	13.25	47.5	18.1	11.499
18	2.89	27.40	2.00	13.70	50.0	18.2	12.397
19	2.94	28.70	2.00	14.35	54.0	18.4	13.332
20	3.00	30.00	2.00	15.00	57.0	18.5	14.311
21	3.04	30.00	1.968	15.24	61.0	18.7	15.303
22	3.09	30.00	1.829	16.40	63.5	18.8	16.252
23	3.14	30.00	1.784	16.82	66.0	18.9	17.155
24	3.18	30.00	1.688	17.77	68.0	19.0	18.023
25	3.22	30.00	1.600	18.75	71.0	19.1	18.845
26	3.26	30.00	1.525	19.67	73.0	19.2	19.626
27	3.30	30.00	1.458	20.58	75.0	19.3	20.372
28	3.33	30.00	1.386	21.65	76.0	19.3	21.083
29	3.37	30.00	1.327	22.61	78.0	19.4	21.761
30	3.40	30.00	1.263	23.75	80.0	19.5	22.409
35	3.56	30.00	0.853	35.17	86.0	19.8	25.054
40	3.69	30.00	0.514	58.37	89.0	20.0	26.763
45	3.81	30.00	0.353	84.99	92.0	20.1	27.846
50	3.91	30.00	0.295	101.69	92.5	20.1	28.656
55	4.01	30.00	0.268	111.94	93.0	20.1	29.360
60	4.09	30.00	0.244	122.95	93.0	20.1	30.000

Electrokinetic Dewatering Test of Humic Sludge (Copper, Constant Current, 50kPa, 500g)

EK Dewatering with Constant Current

Date	5/12/2003		**Initial Solid Concentration**	16.2	%
Pressure	50	kPa	**Mass of Sample**	500	g

		1.0A					
Time (min)	**Log Time**	**Voltage (V)**	**Current (A)**	**Resistance (Ohm)**	**Volume (ml)**	**Solid Concentration (%)**	**Power Consumption (Wh)**
1	0.00	7.39	1.000	7.39	0.0	16.2	0.123
2	0.69	7.52	1.000	7.52	0.0	16.2	0.247
3	1.10	7.68	1.000	7.68	0.0	16.2	0.374
4	1.39	7.82	1.000	7.82	0.0	16.2	0.503
5	1.61	7.96	1.000	7.96	0.0	16.2	0.635
6	1.79	8.06	1.000	8.06	0.0	16 2	0.768
7	1.95	8.18	1.000	8.18	0.0	16.2	0.904
8	2.08	8.14	1.000	8.14	0.0	16.2	1.040
9	2.20	8.18	1.000	8.18	0.0	16.2	1.176
10	2.30	8.22	1.000	8.22	1.0	16.2	1.312
11	2.40	8.27	1.000	8.27	2.0	16.3	1.450
12	2.48	8.33	1.000	8.33	3.0	16.3	1.588
13	2.56	8.28	1.000	8.28	4.0	16.3	1.726
14	2.64	8.32	1.000	8.32	5.0	16.4	1.865
15	2.71	8.39	1.000	8.39	6.0	16.4	2.004
16	2.77	8.42	1.000	8.42	7.0	16.4	2.144
17	2.83	8.48	1.000	8.48	8.0	16.5	2.285
18	2.89	8.55	1.000	8.55	9.0	16.5	2.427
19	2.94	8.61	1.000	8.61	10.5	16.5	2.570
20	3.00	8.68	1.000	8.68	12.0	16.6	2.714
21	3.04	8.75	1.000	8.75	14.0	16.7	2.859
22	3.09	8.82	1.000	8.82	15.5	16.7	3.006
23	3.14	8.88	1.000	8.88	17.5	16.8	3.153
24	3.18	8.95	1.000	8.95	19.0	16.8	3.302
25	3.22	9.02	1.000	9.02	20.5	16.9	3.451
26	3.26	9.09	1.000	9.09	22.0	16.9	3.602
27	3.30	9.19	1.000	9.19	24.0	17.0	3.755
28	3 33	9.27	1.000	9.27	26.0	17.1	3.909
29	3.37	9.02	1.000	9 02	30.0	17.2	4.061
30	3.40	9.05	1.000	9.05	32.0	17.3	4.212
35	3.56	9.54	1.000	9.54	43.0	17.7	4.986
40	3.69	10.03	1.000	10.03	53 0	18.1	5.802
45	3.81	10.42	1.000	10.42	64.0	18.6	6.654
50	3.91	10.84	1.000	10.84	75.0	19.1	7.539
55	4.01	11.42	1.000	11.42	84.5	19 5	8.467
60	4.09	12.15	1.000	12.15	95.5	20.0	9.449
75	4.32	16.69	1.000	16.69	128.0	21.8	13.054
90	4.50	20.70	1.000	20.70	161.0	23.9	17.728
105	4.65	30 00	0.753	39.84	180.0	25.3	23.283
120	4.79	30.00	0.544	55.15	195.0	26 6	28.146

Electrokinetic Dewatering Test of Humic Sludge (Copper, Constant Current, 50kPa, 500g)

EK Dewatering with Constant Current

Date	26/11/2003		**Initial Solid Concentration**	15.4	%
Pressure	50	kPa	**Mass of Sample**	500	g

		2.0A					
Time (min)	Log Time	Voltage (V)	Current (A)	Resistance (Ohm)	Volume (ml)	Solid Concentration (%)	Power Consumption (Wh)
1	0.00	14.25	2.00	7.13	0.0	15.4	0.475
2	0.69	14.72	2.00	7.36	0.0	15.4	0.958
3	1.10	14.82	2.00	7.41	0.0	15.4	1.450
4	1.39	15.02	2.00	7.51	0.0	15.4	1.948
5	1.61	15.16	2.00	7.58	1.0	15.4	2.451
6	1.79	15.28	2.00	7.64	5.0	15.6	2.958
7	1.95	15.47	2.00	7.74	10.0	15.7	3.470
8	2.08	15.64	2.00	7.82	15.5	15.9	3.989
9	2.20	15.80	2.00	7.90	19.5	16.0	4.513
10	2.30	15.99	2.00	8.00	23.5	16.2	5.043
11	2.40	16.08	2.00	8.04	28.0	16.3	5.577
12	2.48	16.30	2.00	8.15	33.0	16.5	6.117
13	2.56	16.48	2.00	8.24	38.0	16.7	6.663
14	2.64	16.72	2.00	8.36	42.0	16.8	7.217
15	2.71	16.80	2.00	8.40	47.0	17.0	7.775
16	2.77	16.90	2.00	8.45	52.0	17.2	8.337
17	2.83	17.14	2.00	8.57	56.5	17.4	8.904
18	2.89	17.17	2.00	8.59	61.0	17.5	9.476
19	2.94	17.23	2.00	8.62	65.5	17.7	10.049
20	3.00	17.36	2.00	8.68	69.5	17.9	10.626
21	3.04	17.45	2.00	8.73	74.0	18.1	11.206
22	3.09	17.55	2.00	8.78	79.0	18.3	11.789
23	3.14	17.75	2.00	8.88	83.5	18.5	12.378
24	3.18	17.93	2.00	8.97	88.0	18.7	12.972
25	3.22	18.11	2.00	9.06	92.0	18.9	13.573
26	3.26	18.25	2.00	9.13	96.5	19.1	14.179
27	3.30	18.48	2.00	9.24	101.0	19.3	14.791
28	3.33	18.77	2.00	9.39	105.5	19.5	15.412
29	3.37	19.05	2.00	9.53	110.0	19.7	16.042
30	3.40	19.40	2.00	9.70	114.0	19.9	16.683
35	3.56	23.40	2.00	11.70	136.0	21.2	20.250
40	3.69	26.00	2.00	13.00	160.0	22.6	24.367
45	3.81	30.00	1.971	15.22	185.0	24.4	28.999
50	3.91	30.00	1.255	23.90	201.0	25.8	33.032
55	4.01	30.00	0.909	33.00	213.0	26.8	35.737
60	4.09	30.00	0.735	40.82	223.0	27.8	37.792

Electrokinetic Dewatering Test of Humic Sludge (Copper, Constant Current, 75kPa, 500g)

EK Dewatering with Constant Current

Date	28/11/2003		**Initial Solid Concentration**	16.1	%
Pressure	75	kPa	**Mass of Sample**	500	g

		1.0A					
Time (min)	**Log Time**	**Voltage (V)**	**Current (A)**	**Resistance (Ohm)**	**Volume (ml)**	**Solid Concentration (%)**	**Power Consumption (Wh)**
1	0.00	6.89	1.000	6.89	0.0	16.1	0.115
2	0.69	7.34	1.000	7.34	0.0	16.1	0.233
3	1.10	7.55	1.000	7.55	0.0	16.1	0.358
4	1.39	7.70	1.000	7.70	0.0	16.1	0.485
5	1.61	7.82	1.000	7.82	0.0	16.1	0.614
6	1.79	7.91	1.000	7.91	0.0	16.1	0.745
7	1.95	8.01	1.000	8.01	0.0	16.1	0.878
8	2.08	8.09	1.000	8 09	0.0	16.1	1.012
9	2.20	8.21	1.000	8.21	2.0	16.2	1.148
10	2.30	8.28	1.000	8.28	4.0	16.2	1.285
11	2.40	8.37	1.000	8.37	6.0	16.3	1.424
12	2.48	8.44	1.000	8.44	7.0	16.3	1.564
13	2.56	8.53	1.000	8.53	9.0	16.4	1.705
14	2.64	8.48	1.000	8.48	11.0	16.5	1.847
15	2.71	8.59	1.000	8.59	11.5	16.5	1.989
16	2.77	8.66	1.000	8.66	13.5	16.5	2.133
17	2.83	8.73	1.000	8.73	14.5	16.6	2.278
18	2.89	8.84	1.000	8.84	16.0	16.6	2.424
19	2.94	8.93	1.000	8.93	18.0	16.7	2.573
20	3.00	9.02	1.000	9.02	19.0	16.7	2.722
21	3.04	9.15	1.000	9.15	21.0	16.8	2.874
22	3.09	9.13	1.000	9.13	23.0	16.9	3.026
23	3.14	9.27	1.000	9.27	25.0	16.9	3.179
24	3.18	9.38	1.000	9.38	27.0	17.0	3.335
25	3.22	9 49	1.000	9.49	30.0	17.1	3.492
26	3.26	9.60	1.000	9 60	32.0	17.2	3.651
27	3.30	9.71	1.000	9.71	34.0	17.3	3.812
28	3.33	9.84	1.000	9.84	36.0	17.3	3.975
29	3.37	9.95	1.000	9.95	38.0	17.4	4.140
30	3.40	9 94	1.000	9.94	41.0	17.5	4.305
35	3.56	10.47	1.000	10.47	53.0	18.0	5.156
40	3.69	10 98	1.000	10 98	66.0	18.5	6.050
45	3 81	11.43	1.000	11.43	79 0	19.1	6.983
50	3.91	11.87	1.000	11.87	92.0	19.7	7.954
55	4.01	12.67	1.000	12.67	105.0	20.4	8.977
60	4 09	14.00	1.000	14.00	118.0	21.1	10.088
75	4.32	17.66	1.000	17.66	162.0	23.8	14.045
90	4.50	26 90	1.000	26.90	196.0	26 5	19.615
105	4 65	30.00	0.657	45.66	224.0	29.2	25.508
120	4.79	30.00	0 436	68 81	243.0	31.3	29.607

Electrokinetic Dewatering Test of Humic Sludge (Copper, Constant Current, 75kPa, 500g)

EK Dewatering with Constant Current

Date	20/11/2003		**Initial Solid Concentration**	15.5	%
Pressure	75	kPa	**Mass of Sample**	500	g

		2.0A					
Time (min)	Log Time	Voltage (V)	Current (A)	Resistance (Ohm)	Volume (ml)	Solid Concentration (%)	Power Consumption (Wh)
1	0.00	14.53	2.00	7.27	0.0	15.5	0.484
2	0.69	15.10	2.00	7.55	0.0	15.5	0.978
3	1.10	15.34	2.00	7.67	0.0	15.5	1.486
4	1.39	15.46	2.00	7.73	0.0	15.5	1.999
5	1.61	15.59	2.00	7.80	3.0	15.6	2.516
6	1.79	15.76	2.00	7.88	9.0	15.8	3.039
7	1.95	15.99	2.00	8.00	15.0	16.0	3.568
8	2.08	16.17	2.00	8.09	22.0	16.2	4.104
9	2.20	16.38	2.00	8.19	28.0	16.4	4.647
10	2.30	16.62	2.00	8.31	34.0	16.6	5.197
11	2.40	16.79	2.00	8.40	40.0	16.8	5.753
12	2.48	16.88	2.00	8.44	46.0	17.1	6.315
13	2.56	17.12	2.00	8.56	51.0	17.3	6.881
14	2.64	17.29	2.00	8.65	56.0	17.5	7.455
15	2.71	17.43	2.00	8.72	61.0	17.7	8.033
16	2.77	17.54	2.00	8.77	67.0	17.9	8.616
17	2.83	17.70	2.00	8.85	72.0	18.1	9.204
18	2.89	17.83	2.00	8.92	77.0	18.3	9.796
19	2.94	17.97	2.00	8.99	82.5	18.6	10.392
20	3.00	18.14	2.00	9.07	88.0	18.8	10.994
21	3.04	18.29	2.00	9.15	93.0	19.0	11.601
22	3.09	18.49	2.00	9.25	98.0	19.3	12.214
23	3.14	18.62	2.00	9.31	103.0	19.5	12.833
24	3.18	18.91	2.00	9.46	108.0	19.8	13.458
25	3.22	19.17	2.00	9.59	113.0	20.0	14.093
26	3.26	19.60	2.00	9.80	117.5	20.3	14.739
27	3.30	19.90	2.00	9.95	122.5	20.5	15.398
28	3.33	20.80	2.00	10.40	127.0	20.8	16.076
29	3.37	21.50	2.00	10.75	131.5	21.0	16.781
30	3.40	22.40	2.00	11.20	136.0	21.3	17.513
35	3.56	25.80	2.00	12.90	161.0	22.9	21.529
40	3.69	29.80	2.00	14.90	187.0	24.8	26.163
45	3.81	30.00	1.304	23.01	205.0	26.3	30.279
50	3.91	30.00	0.985	30.46	217.0	27.4	33.140
55	4.01	30.00	0.787	38.12	226.0	28.3	35.355
60	4.09	30.00	0.649	46.22	235.0	29.2	37.150

Electrokinetic Dewatering Test of Humic Sludge (Copper, Constant Current, 25kPa, 500g)

EK Dewatering with Constant Current

Date	8/12/2003		**Initial Solid Concentration**	16.1	%
Pressure	25	kPa	**Mass of Sample**	500	g

		Control					
Time (min)	**Log Time**	**Voltage (V)**	**Current (A)**	**Resistance (Ohm)**	**Volume (ml)**	**Solid Concentration (%)**	**Power Consumption (Wh)**
1	0.00	0.00	0.000	-	0.0	16.1	0.000
5	1.61	0.00	0.000	-	0.0	16.1	0.000
10	2.30	0.00	0.000	-	0.0	16.1	0.000
15	2.71	0.00	0.000	-	0.0	16.1	0.000
20	3.00	0.00	0.000	-	0.0	16.1	0.000
25	3.22	0.00	0.000	-	0.0	16.1	0.000
30	3.40	0.00	0.000	-	0.0	16.1	0.000
35	3.56	0.00	0.000	-	0.0	16.1	0.000
40	3.69	0.00	0.000	-	0.0	16.1	0.000
45	3.81	0.00	0.000	-	0.0	16.1	0.000
50	3.91	0.00	0.000	-	0.0	16.1	0.000
55	4.01	0.00	0.000	-	0.0	16.1	0.000
60	4.09	0.00	0.000	-	0.0	16.1	0.000

Electrokinetic Dewatering Test of Humic Sludge (Copper, Constant Current, 50kPa, 500g)

EK Dewatering with Constant Current

Date 5/12/2003

Pressure 50 kPa

Initial Solid Concentration 16.2 %

Mass of Sample 500 g

		Control					
Time (min)	Log Time	Voltage (V)	Current (A)	Resistance (Ohm)	Volume (ml)	Solid Concentration (%)	Power Consumption (Wh)
1	0.00	0.00	0.000	-	0.0	16.2	0.000
5	1.61	0.00	0.000	-	0.0	16.2	0.000
10	2.30	0.00	0.000	-	0.0	16.2	0.000
15	2.71	0.00	0.000	-	0.0	16.2	0.000
20	3.00	0.00	0.000	-	0.0	16.2	0.000
25	3.22	0.00	0.000	-	1.5	16.2	0.000
30	3.40	0.00	0.000	-	4.0	16.3	0.000
35	3.56	0.00	0.000	-	5.5	16.4	0.000
40	3.69	0.00	0.000	-	7.0	16.4	0.000
45	3.81	0.00	0.000	-	8.5	16.5	0.000
50	3.91	0.00	0.000	-	10.0	16.5	0.000
55	4.01	0.00	0.000	-	11.5	16.6	0.000
60	4.09	0.00	0.000	-	13.0	16.6	0.000

Electrokinetic Dewatering Test of Humic Sludge (Copper, Constant Current, 75kPa, 500g)

EK Dewatering with Constant Current

Date	28/11/2003		**Initial Solid Concentration**	16.1	%
Pressure	75	kPa	**Mass of Sample**	500	g

		Control					
Time (min)	**Log Time**	**Voltage (V)**	**Current (A)**	**Resistance (Ohm)**	**Volume (ml)**	**Solid Concentration (%)**	**Power Consumption (Wh)**
1	0.00	0.00	0.000	-	0.0	16.1	0.000
5	1.61	0.00	0.000	-	0.0	16.1	0.000
10	2.30	0.00	0.000	-	0.0	16.1	0.000
15	2.71	0.00	0.000	-	0.0	16.1	0.000
20	3.00	0.00	0.000	-	2.0	16.2	0.000
25	3.22	0.00	0.000	-	4.0	16.2	0.000
30	3.40	0.00	0.000	-	6.0	16.3	0.000
35	3.56	0.00	0.000	-	8.0	16.4	0.000
40	3.69	0.00	0.000	-	10.0	16.4	0.000
45	3.81	0.00	0.000	-	11.5	16.5	0.000
50	3.91	0.00	0.000	-	13.0	16.5	0.000
55	4.01	0.00	0.000	-	14.0	16.6	0.000
60	4.09	0.00	0.000	-	15.5	16.6	0.000

Electrokinetic Dewatering Test of Humic Sludge (Copper, Constant Current, 25kPa, 250g)

EK Dewatering with Constant Current

Date	13/11/2003		**Initial Solid Concentration**	16.8	%
Pressure	25	kPa	**Mass of Sample**	250	g

		2.0A					
Time (min)	Log Time	Voltage (V)	Current (A)	Resistance (Ohm)	Volume (ml)	Solid Concentration (%)	Power Consumption (Wh)
1	0.00	7.96	2.00	3.98	0.0	16.8	0.265
2	0.69	8.78	2.00	4.39	0.0	16.8	0.544
3	1.10	9.38	2.00	4.69	0.0	16.8	0.847
4	1.39	9.85	2.00	4.93	0.0	16.8	1.168
5	1.61	10.22	2.00	5.11	0.0	16.8	1.502
6	1.79	10.67	2.00	5.34	0.0	16.8	1.850
7	1.95	11.08	2.00	5.54	0.0	16.8	2.213
8	2.08	11.66	2.00	5.83	3.0	17.0	2.592
9	2.20	12.20	2.00	6.10	7.0	17.3	2.989
10	2.30	12.79	2.00	6.40	11.0	17.6	3.406
11	2.40	13.40	2.00	6.70	15.0	17.9	3.842
12	2.48	14.08	2.00	7.04	18.0	18.1	4.300
13	2.56	14.95	2.00	7.48	21.0	18.3	4.784
14	2.64	16.09	2.00	8.05	24.0	18.6	5.302
15	2.71	17.33	2.00	8.67	28.0	18.9	5.859
16	2.77	18.80	2.00	9.40	32.0	19.3	6.461
17	2.83	20.20	2.00	10.10	35.0	19.5	7.111
18	2.89	21.90	2.00	10.95	38.0	19.8	7.812
19	2.94	24.30	2.00	12.15	41.0	20.1	8.582
20	3.00	27.70	2.00	13.85	44.0	20.4	9.449
21	3.04	30.00	1.814	16.54	47.5	20.7	10.366
22	3.09	30.00	1.555	19.29	49.5	20.9	11.208
23	3.14	30.00	1.378	21.77	50.5	21.1	11.941
24	3.18	30.00	1.246	24.08	51.5	21.2	12.597
25	3.22	30.00	1.127	26.62	52.5	21.3	13.191
26	3.26	30.00	1.041	28.82	53.5	21.4	13.733
27	3.30	30.00	0.958	31.32	54.5	21.5	14.232
28	3.33	30.00	0 882	34.01	56.0	21.6	14.692
29	3.37	30.00	0.829	36.19	57.0	21.8	15.120
30	3.40	30.00	0.764	39.27	58.0	21.9	15.518
35	3.56	30.00	0.586	51.19	61.0	22.2	17.206
40	3.69	30.00	0.497	60.36	62.0	22.3	18.560
45	3.81	30.00	0.452	66.37	62.0	22.3	19.746
50	3.91	30.00	0.412	72.82	62.0	22.3	20.826
55	4.01	30.00	0.366	81.97	62.0	22.3	21.798
60	4 09	30.00	0.349	85.96	62.0	22.3	22.692

Electrokinetic Dewatering Test of Humic Sludge (Copper, Constant Current, 50kPa, 250g)

EK Dewatering with Constant Current

Date	27/11/2003	**Initial Solid Concentration**	15.9 %
Pressure	50 kPa	**Mass of Sample**	250 g

		2.0A					
Time (min)	Log Time	Voltage (V)	Current (A)	Resistance (Ohm)	Volume (ml)	Solid Concentration (%)	Power Consumption (Wh)
1	0.00	8.29	2.00	4.15	0.0	15.9	0.276
2	0.69	8.86	2.00	4.43	0.0	15.9	0.562
3	1.10	9.24	2.00	4.62	0.0	15.9	0.864
4	1.39	9.54	2.00	4.77	0.0	15.9	1.177
5	1.61	9.78	2.00	4.89	0.0	15.9	1.499
6	1.79	10.08	2.00	5.04	3.0	16.1	1.830
7	1.95	10.41	2.00	5.21	8.0	16.4	2.171
8	2.08	10.75	2.00	5.38	12.0	16.7	2.524
9	2.20	11.07	2.00	5.54	17.0	17.1	2.888
10	2.30	11.39	2.00	5.70	21.0	17.4	3.262
11	2.40	11.81	2.00	5.91	25.5	17.7	3.649
12	2.48	12.26	2.00	6.13	29.5	18.0	4.050
13	2.56	12.66	2.00	6.33	34.0	18.4	4.465
14	2.64	13.50	2.00	6.75	38.0	18.8	4.901
15	2.71	14.44	2.00	7.22	42.5	19.2	5.367
16	2.77	15.51	2.00	7.76	47.0	19.6	5.866
17	2.83	16.44	2.00	8.22	51.5	20.0	6.399
18	2.89	17.20	2.00	8.60	55.5	20.4	6.959
19	2.94	18.08	2.00	9.04	60.0	20.9	7.547
20	3.00	19.12	2.00	9.56	64.0	21.4	8.167
21	3.04	21.00	2.00	10.50	68.5	21.9	8.836
22	3.09	23.20	2.00	11.60	72.0	22.3	9.573
23	3.14	26.10	2.00	13.05	76.5	22.9	10.394
24	3.18	29.00	2.00	14.50	81.0	23.5	11.313
25	3.22	30.00	1.866	16.08	84.0	23.9	12.263
26	3.26	30.00	1.707	17.57	87.0	24.4	13.156
27	3.30	30.00	1.570	19.11	89.0	24.7	13.975
28	3.33	30.00	1.449	20.70	91.0	25.0	14.730
29	3.37	30.00	1.337	22.44	93.0	25.3	15.427
30	3.40	30.00	1.225	24.49	95.0	25.6	16.067
35	3.56	30.00	0.866	34.64	101.0	26.7	18.681
40	3.69	30.00	0.662	45.32	106.0	27.6	20.591
45	3.81	30.00	0.548	54.74	109.5	28.3	22.103
50	3.91	30.00	0.470	63.83	111.0	28.6	23.376
55	4.01	30.00	0.411	72.99	112.0	28.8	24.477
60	4.09	30.00	0.371	80.86	112.5	28.9	25.455

Electrokinetic Dewatering Test of Humic Sludge (Copper, Constant Current, 75kPa, 250g)

EK Dewatering with Constant Current

Date : 21/11/2003 **Initial Solid Concentration** 15.9 %

Pressure 75 kPa **Mass of Sample** 250 g

		2.0A					
Time (min)	Log Time	Voltage (V)	Current (A)	Resistance (Ohm)	Volume (ml)	Solid Concentration (%)	Power Consumption (Wh)
1	0.00	8.69	2.00	4.35	0.0	15.9	0.290
2	0.69	9.38	2.00	4.69	0.0	15.9	0.591
3	1.10	9.83	2.00	4.92	0.0	15.9	0.911
4	1.39	10.10	2.00	5.05	0.0	15.9	1.243
5	1.61	10.34	2.00	5.17	1.0	16.0	1.584
6	1.79	10.63	2.00	5.32	7.0	16.4	1.933
7	1.95	11.04	2.00	5.52	10.0	16.6	2.295
8	2.08	11.36	2.00	5.68	14.0	16.8	2.668
9	2.20	11.81	2.00	5.91	17.5	17.1	3.054
10	2.30	12.21	2.00	6.11	24.0	17.6	3.454
11	2.40	12.79	2.00	6.40	29.0	18.0	3.871
12	2.48	13.42	2.00	6.71	34.0	18.4	4.308
13	2.56	14.07	2.00	7.04	40.0	18.9	4.766
14	2.64	14.81	2.00	7.41	46.0	19.5	5.247
15	2.71	15.70	2.00	7.85	52.0	20.1	5.756
16	2.77	16.46	2.00	8.23	58.0	20.7	6.292
17	2.83	17.36	2.00	8.68	64.0	21.4	6.856
18	2.89	18.08	2.00	9.04	69.5	22.0	7.446
19	2.94	19.14	2.00	9.57	75.0	22.7	8.067
20	3.00	20.50	2.00	10.25	80.0	23.4	8.727
21	3.04	22.60	2.00	11.30	84.0	23.9	9.446
22	3.09	26.00	2.00	13.00	88.5	24.6	10.256
23	3.14	30.00	1.991	15.07	93.0	25.3	11.187
24	3.18	30.00	1.748	17.16	96.5	25.9	12.121
25	3.22	30.00	1.541	19.47	100.0	26.5	12.944
26	3.26	30.00	1.399	21.44	103.5	27.1	13.679
27	3.30	30.00	1.277	23.49	106.0	27.6	14.348
28	3.33	30.00	1.155	25.97	108.0	28.0	14.956
29	3.37	30.00	1.063	28.22	109.5	28.3	15.510
30	3.40	30.00	0.975	30.77	111.0	28.6	16.020
35	3.56	30.00	0.688	43.60	117.5	30.0	18.098
40	3.69	30.00	0.550	54.55	119.5	30.5	19.646
45	3.81	30.00	0.464	64.66	121.0	30.8	20.913
50	3.91	30.00	0.407	73.71	122.0	31.1	22.002
55	4.01	30.00	0.365	82.19	122.5	31.2	22.967
60	4.09	30.00	0.334	89.82	123.0	31.3	23.841

Electrokinetic Dewatering Test of Humic Sludge (Carbon, Constant Current, 25kPa & 500g)

EK Dewatering with Constant Current

Date	3/7/2003		**Initial Solid Concentration**	15.5	%
Pressure	25	kPa	**Mass of Sample**	500	g

		2.0A					
Time (min)	Log Time	Voltage (V)	Current (A)	Resistance (Ohm)	Volume (ml)	Solid Concentration (%)	Power Consumption (Wh)
1	0.00	18.64	2.00	9.32	0.0	15.5	0.621
2	0.69	18.83	2.00	9.42	0.0	15.5	1.246
3	1.10	19.10	2.00	9.55	0.0	15.5	1.878
4	1.39	19.70	2.00	9.85	0.0	15.5	2.525
5	1.61	19.90	2.00	9.95	4.0	15.6	3.185
6	1.79	20.10	2.00	10.05	7.0	15.7	3.851
7	1.95	20.30	2.00	10.15	10.0	15.8	4.525
8	2.08	20.40	2.00	10.20	13.5	15.9	5.203
9	2.20	20.60	2.00	10.30	17.5	16.1	5.886
10	2.30	20.80	2.00	10.40	22.5	16.2	6.576
11	2.40	20.90	2.00	10.45	27.5	16.4	7.271
12	2.48	21.10	2.00	10.55	32.5	16.6	7.971
13	2.56	21.30	2.00	10.65	37.5	16.8	8.678
14	2.64	21.40	2.00	10.70	42.5	16.9	9.390
15	2.71	21.60	2.00	10.80	47.5	17.1	10.106
16	2.77	21.70	2.00	10.85	53.0	17.3	10.828
17	2.83	21.90	2.00	10.95	58.0	17.5	11.555
18	2.89	22.10	2.00	11.05	63.5	17.8	12.288
19	2.94	22.30	2.00	11.15	69.0	18.0	13.028
20	3.00	22.70	2.00	11.35	73.5	18.2	13.778
21	3.04	23.00	2.00	11.50	77.5	18.3	14.540
22	3.09	23.20	2.00	11.60	81.5	18.5	15.310
23	3.14	23.50	2.00	11.75	86.5	18.7	16.088
24	3.18	23.90	2.00	11.95	91.0	18.9	16.878
25	3.22	24.20	2.00	12.10	96.0	19.2	17.680
26	3.26	24.70	2.00	12.35	101.0	19.4	18.495
27	3.30	25.40	2.00	12.70	105.5	19.6	19.330
28	3.33	26.40	2.00	13.20	110.0	19.9	20.193
29	3.37	27.30	2.00	13.65	115.0	20.1	21.088
30	3.40	28.30	2.00	14.15	119.0	20.3	22.015
35	3.56	30.00	1.74	17.24	141.0	21.6	26.557
40	3.69	30.00	1.18	25.42	157.0	22.6	30.207
45	3.81	30.00	0.96	31.32	175.0	23.8	32.880
50	3.91	30.00	0.83	36.32	187.0	24.8	35.110
55	4.01	30.00	0.72	41.84	196.0	25.5	37.038
60	4.09	30.00	0.63	48.00	204.0	26.2	38.716

Electrokinetic Dewatering Test of Humic Sludge with Stepped Current

Applied Pressure	=	25	kPa
Height of Sample	=	30	mm
Mass of Sample	=	507	g
Initial Solid Concentration	=	15.8	%

Time (min)	Current (A)	Voltage (V)	Resistance (Ohm)	Volume (ml)	Total Volume (ml)	Solid Concentration (%)
1	1	10.83	10.83	0.0	0.0	15.8
2	1	11.86	11.86	0.0	0.0	15.8
3	1	12.88	12.88	0.0	0.0	15.8
4	1	11.96	11.96	0.0	0.0	15.8
5	1	11.48	11.48	0.0	0.0	15.8
6	1	11.53	11.53	2.5	2.5	15.9
7	1	11.42	11.42	4.0	4.0	15.9
8	1	11.35	11.35	5.5	5.5	16.0
9	1	11.28	11.28	7.0	7.0	16.0
10	1	11.17	11.17	8.5	8.5	16.1
11	1	11.15	11.15	10.0	10.0	16.1
12	1	11.02	11.02	12.0	12.0	16.2
13	1	10.91	10.91	14.0	14.0	16.2
14	1	10.98	10.98	16.0	16.0	16.3
15	1	10.94	10.94	18.0	18.0	16.4
16	1	11.01	11.01	20.0	20.0	16.4
17	1	11.04	11.04	22.0	22.0	16.5
18	1	11.09	11.09	24.0	24.0	16.6
19	1	11.12	11.12	26.0	26.0	16.7
20	1	11.14	11.14	28.0	28.0	16.7
21	2	21.90	10.95	4.0	32.0	16.9
22	2	22.00	11.00	8.0	36.0	17.0
23	2	22.20	11.10	12.0	40.0	17.2
24	2	22.50	11.25	17.0	45.0	17.3
25	2	22.70	11.35	22.0	50.0	17.5
26	2	22.90	11.45	26.0	54.0	17.7
27	2	22.80	11.40	31.0	59.0	17.9
28	2	22.90	11.45	34.0	62.0	18.0

29	2	23.30	11.65	38.0	66.0	18.2
30	2	23.50	11.75	41.0	69.0	18.3
31	2	23.70	11.85	45.0	73.0	18.5
32	2	23.90	11.95	49.0	77.0	18.6
33	2	24.20	12.10	53.0	81.0	18.8
34	2	24.60	12.30	57.0	85.0	19.0
35	2	25.00	12.50	61.0	89.0	19.2
36	2	25.60	12.80	65.0	93.0	19.3
37	2	26.30	13.15	70.0	98.0	19.6
38	2	27.80	13.90	73.0	101.0	19.7
39	2	28.70	14.35	77.0	105.0	19.9
40	2	29.60	14.80	81.0	109.0	20.1
41	1	15.09	15.09	2.0	111.0	20.2
42	1	15.75	15.75	4.0	113.0	20.3
43	1	15.25	15.25	6.0	115.0	20.4
44	1	15.40	15.40	8.0	117.0	20.5
45	1	15.61	15.61	10.0	119.0	20.6
46	1	15.83	15.83	12.0	121.0	20.8
47	1	16.14	16.14	15.0	124.0	20.9
48	1	16.50	16.50	17.0	126.0	21.0
49	1	16.17	16.17	18.0	127.0	21.1
50	1	17.28	17.28	20.0	129.0	21.2
51	1	17.77	17.77	21.0	130.0	21.2
52	1	18.18	18.18	22.0	131.0	21.3
53	1	18.59	18.59	24.0	133.0	21.4
54	1	19.02	19.02	26.0	135.0	21.5
55	1	19.40	19.40	28.0	137.0	21.7
56	1	19.80	19.80	30.0	139.0	21.8
57	1	20.20	20.20	33.0	142.0	21.9
58	1	20.60	20.60	35.0	144.0	22.1
59	1	21.00	21.00	37.0	146.0	22.2
60	1	21.40	21.40	40.0	149.0	22.4

Electrokinetic Dewatering of Humic Sludge by Constant Current I followed by I / 2

Date	19/3/2004	
Pressure	75	kPa
Mass of Sample	500	g
Solid Content	16.1	%

Experiemental Curve				Predicted Curve			
Time (min)	Voltage (V)	Current (A)	Volume (ml)	Time (min)	Voltage (V)	Current (A)	Volume (ml)
1	14.38	2	0	1	14.53	2	0.0
2	14.95	2	0	2	15.1	2	0.0
3	15.19	2	0	3	15.34	2	0.0
4	15.30	2	0	4	15.46	2	0.0
5	15.43	2	3	5	15.59	2	3.0
6	15.60	2	8	6	15.76	2	9.0
7	15.83	2	15	7	15.99	2	15.0
8	16.01	2	21	8	16.17	2	22.0
9	16.21	2	27.5	9	16.38	2	28.0
10	16.45	2	34	10	16.62	2	34.0
11	16.62	2	39.5	11	16.79	2	40.0
12	16.71	2	45	12	16.88	2	46.0
13	16.95	2	51	13	17.12	2	51.0
14	17.12	2	56.5	14	17.29	2	56.0
15	17.25	2	62	15	17.43	2	61.0
16	17.36	2	68	16	17.54	2	67.0
17	17.52	2	73	17	17.7	2	72.0
18	17.65	2	78	18	17.83	2	77.0
19	17.79	2	83	19	17.97	2	82.5
20	17.96	2	89	20	18.14	2	88.0
21	18.11	2	94	21	18.29	2	93.0
22	18.30	2	99	22	18.49	2	98.0
23	18.43	2	104	23	18.62	2	103.0
24	18.72	2	110	24	18.91	2	108.0
25	18.98	2	115	25	19.17	2	113.0
26	19.40	2	125.5	26	19.6	2	117.5
27	19.70	2	126	27	19.9	2	122.5
28	20.60	2	131	28	20.8	2	127.0